Unbound or Distant planetary mass population detected by Gravitational Microlensing

－Jupiter-mass free-floating planets are common－

Takahiro Sumi (Osaka University)
MOA collaboration
OGLE collaboration

Sumi et al. 2011, Nature, 473, 7347, 349-352

NASA/JPL-Caltech/R. Hurt

Free-floating planet

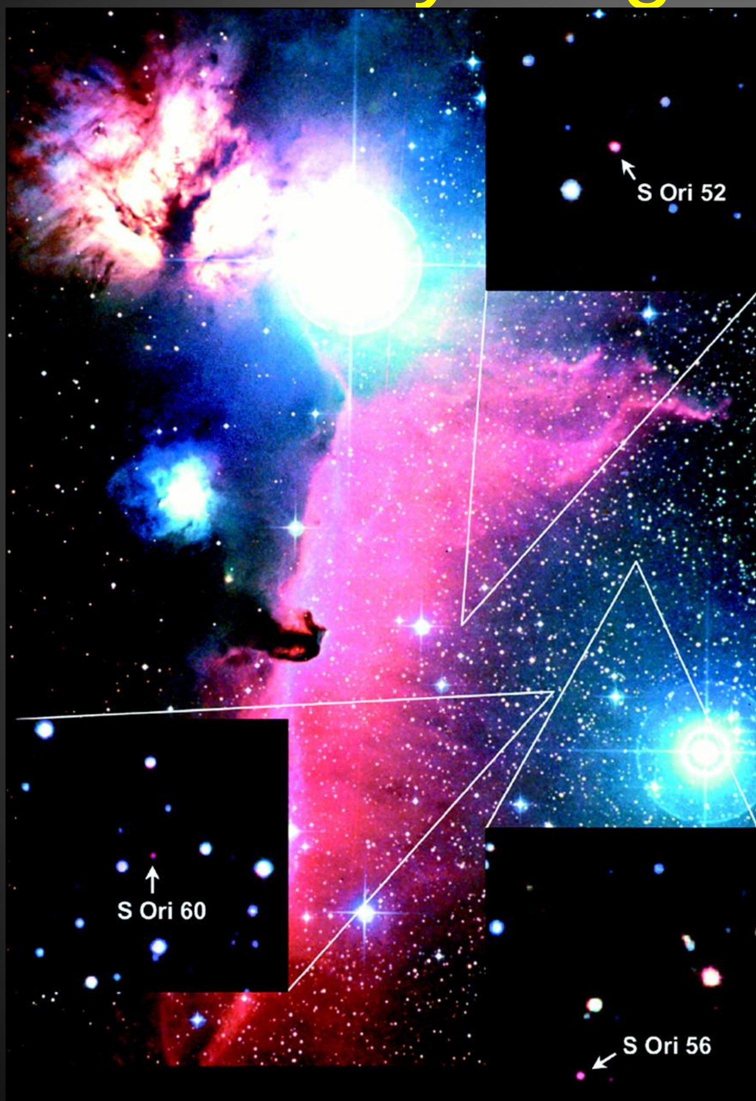
Planetary-mass objects that is not orbiting about any host star called :

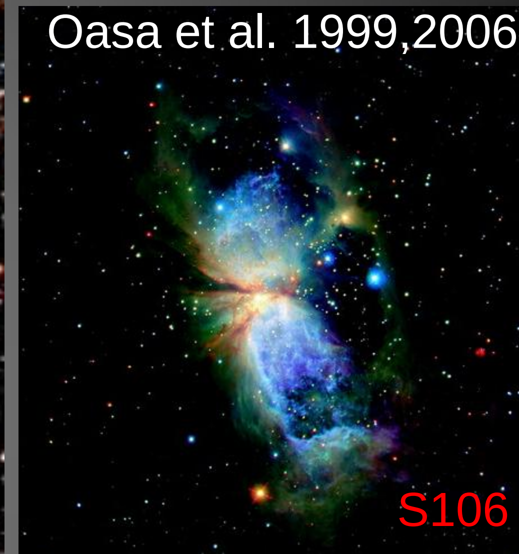
- Free-floating planet
- Rogue planet
- Orphan planet
- Interstellar planet

Can we call them “Planet”? --- still in debate

- If they formed around a host star, and scattered out from orbit, then we may call them a planet.
- However, others believe that the definition of 'planet' should depend on current observable state, and not origin
- They may form on their own through gas cloud collapse similar to star formation; in which case they would never have been planets. →“planetary-mass object” or ” sub brown dwarf”

Free-floating planetary-mass objects in young star forming region

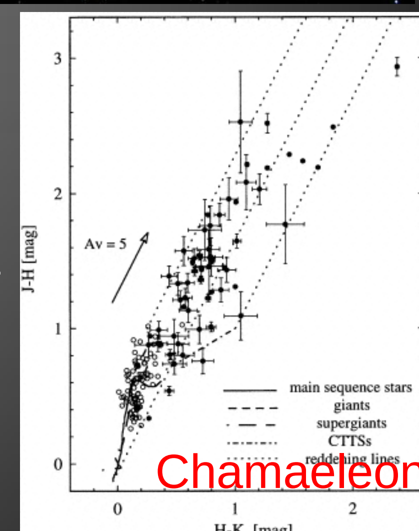




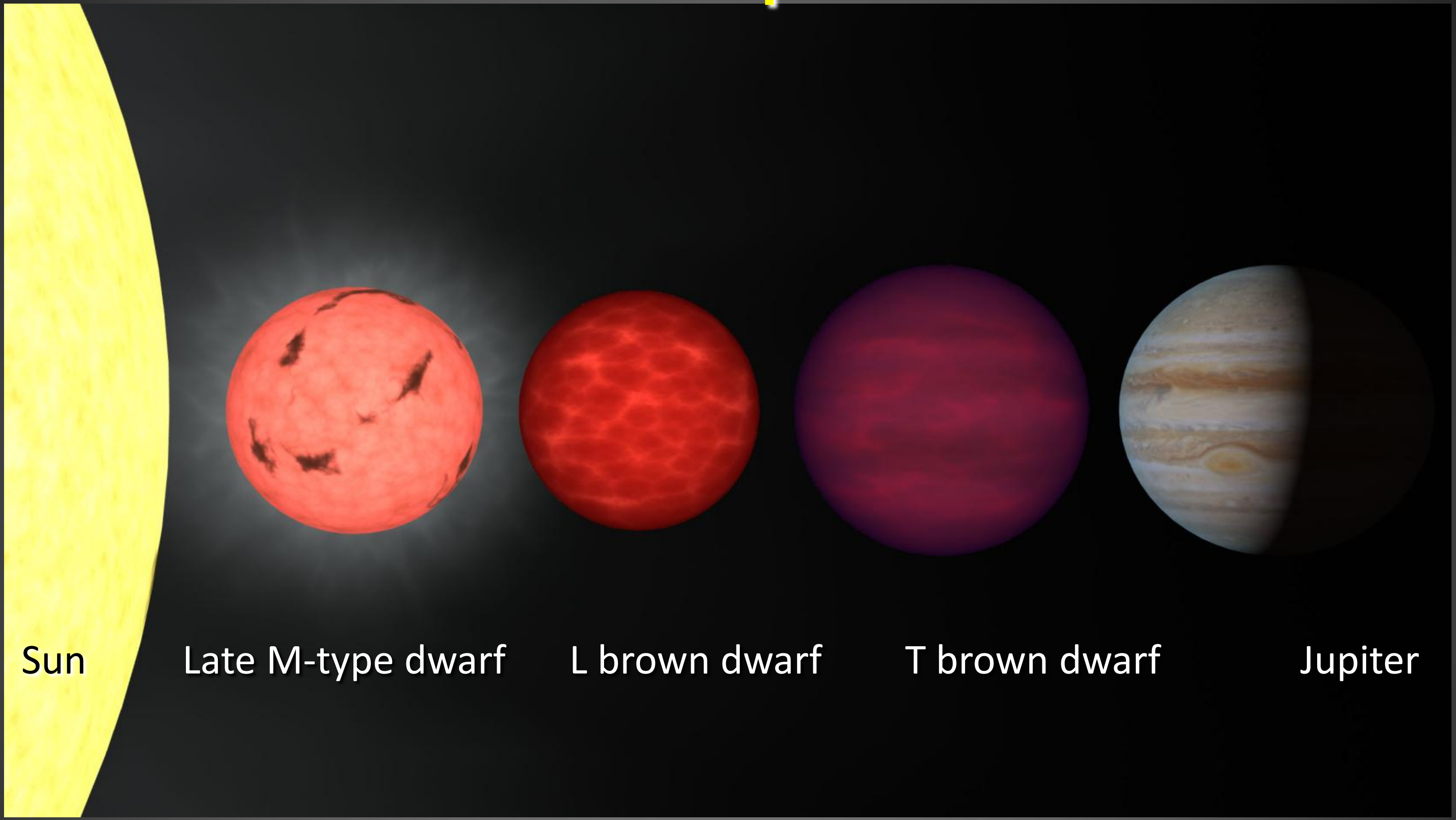
M~5-15 M_J

However, Large uncertainty in

- photometric mass measurement
- their abundance



Size comparison



Mass：１０５０　　７５　　６５　　３０
１ (Jupiter mass)

What we learned about exoplanets?

•The first exoplanet was discovered in 1995.

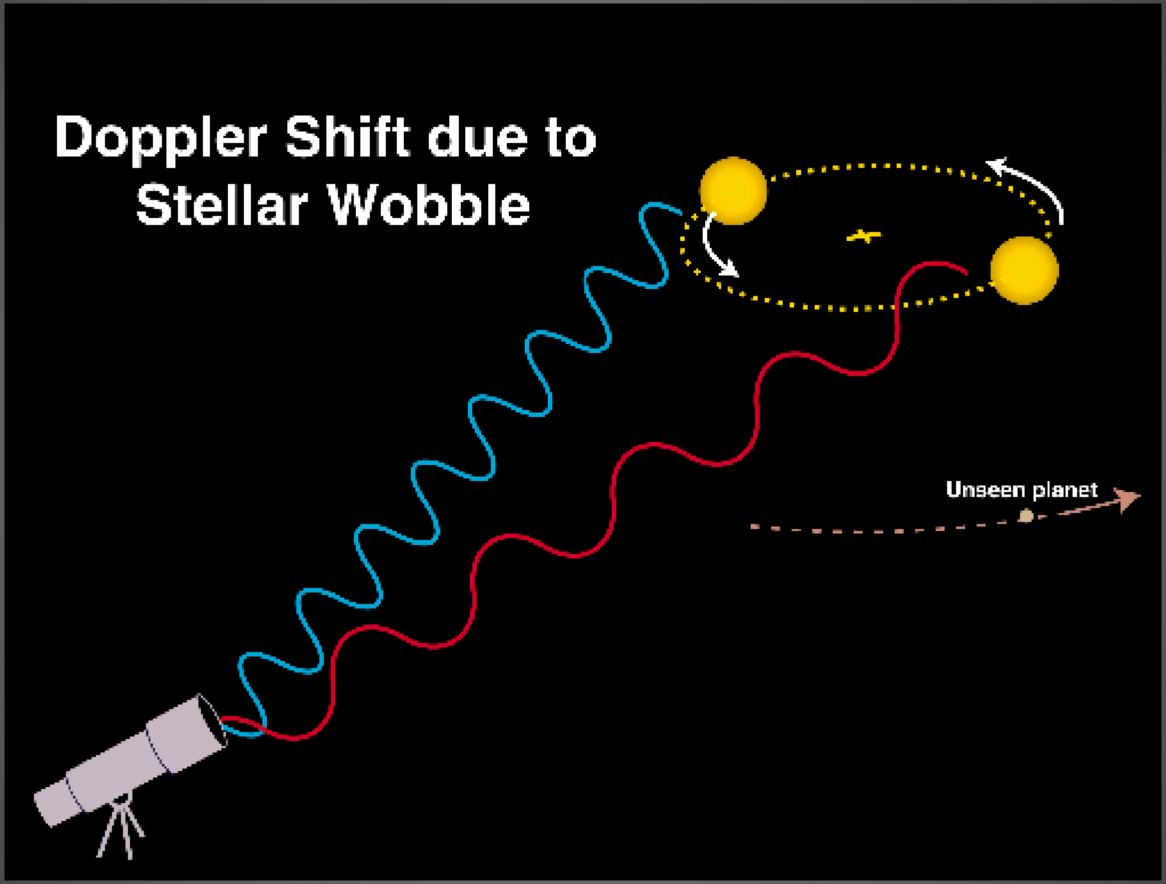
•>５００ exoplanets have been discovered.

•>30% of solar type stars have planets
（>6%–7% of FGK-type stars have one of more gas giant planet within 5AU [Marcy et al. 2005]）

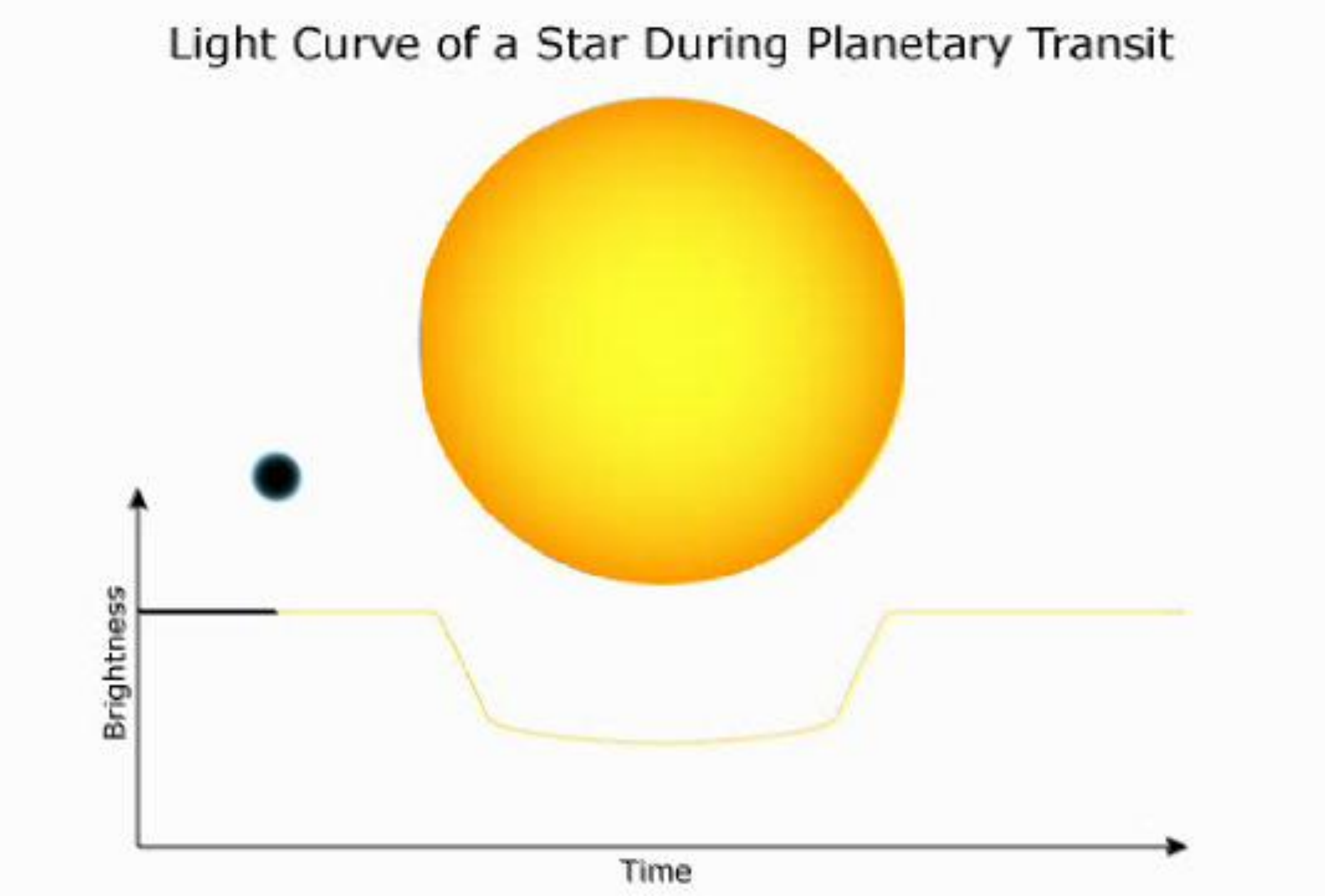
•Variety of planetary systems

•All of them orbit around their host stars
←because they need host stars to be detected

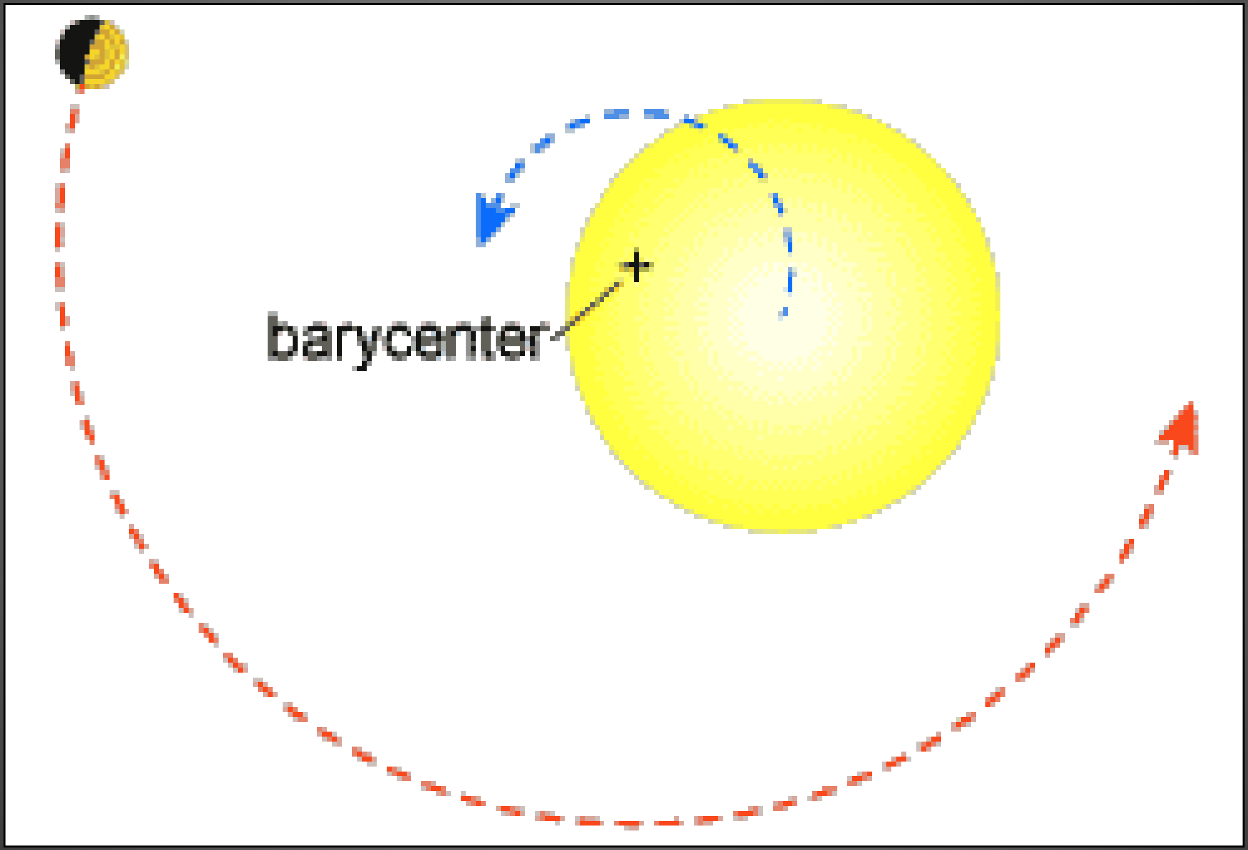
1.Radial Velocity



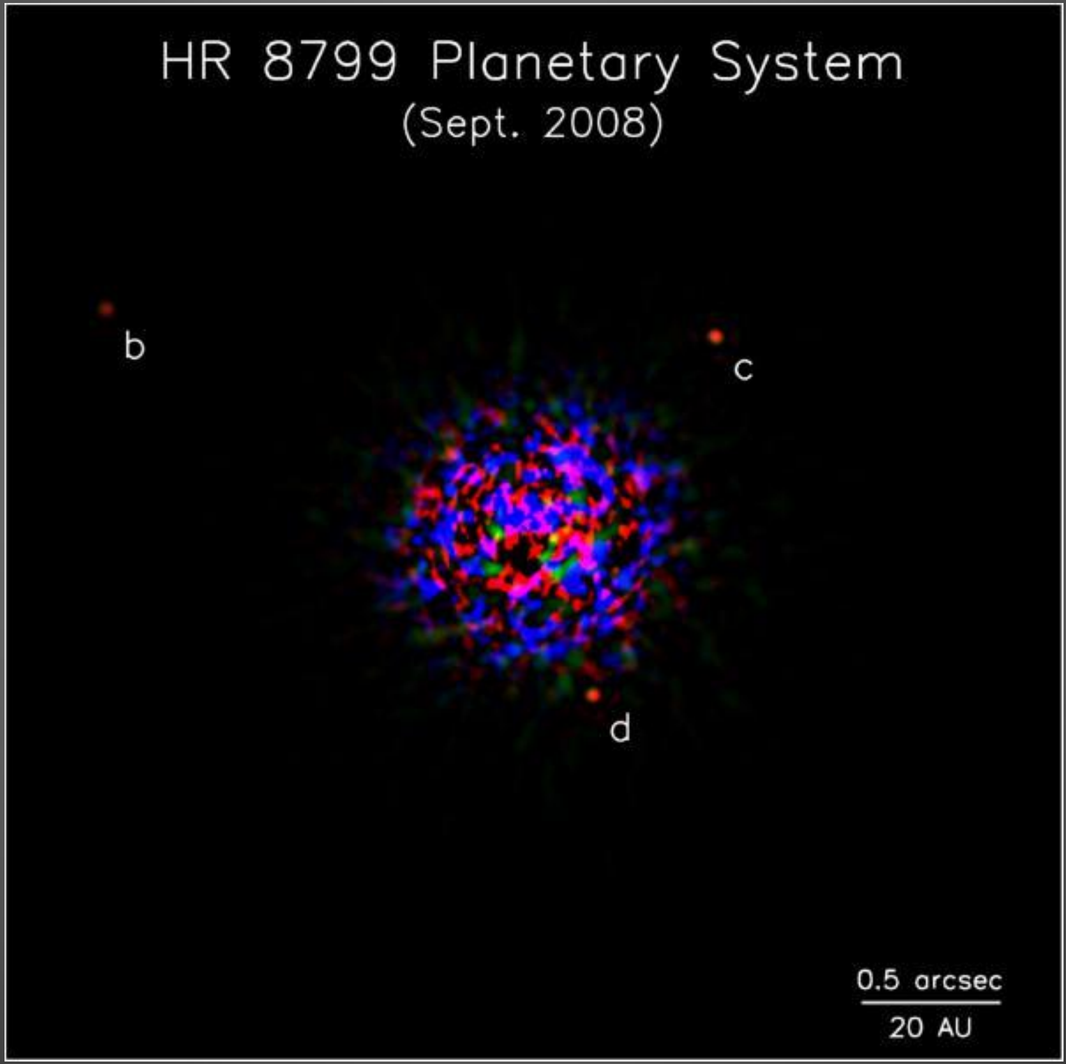
2.Transit


Light Curve of a Star During Planetary Transit
Brightness
Time

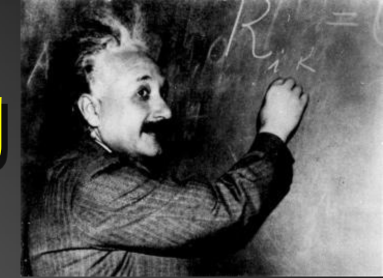
3. Astrometry

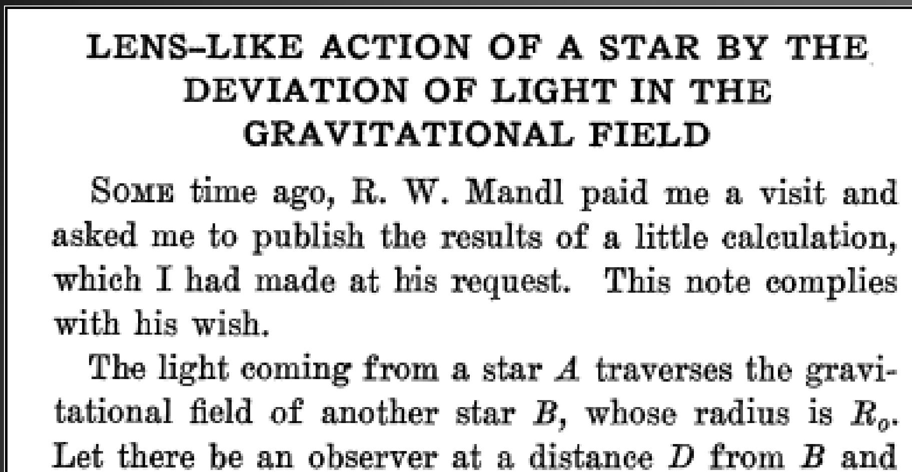


4. Direct imaging



5. Gravitational Microlensing

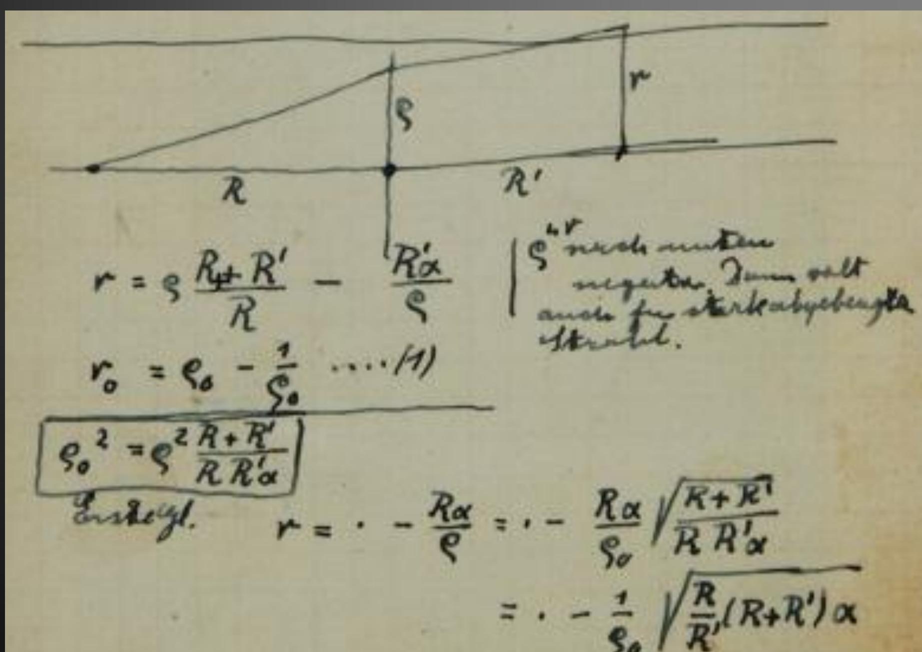




LENS-LIKE ACTION OF A STAR BY THE DEVIATION OF LIGHT IN THE GRAVITATIONAL FIELD

SOME time ago, R. W. Mandl paid me a visit and asked me to publish the results of a little calculation, which I had made at his request. This note complies with his wish.

The light coming from a star A traverses the gravitational field of another star B, whose radius is R_0. Let there be an observer at a distance D from B and



the Collected Papers of Albert Einstein, Vol. 3, p. 585;
Reprinted by permission of Princeton University Press

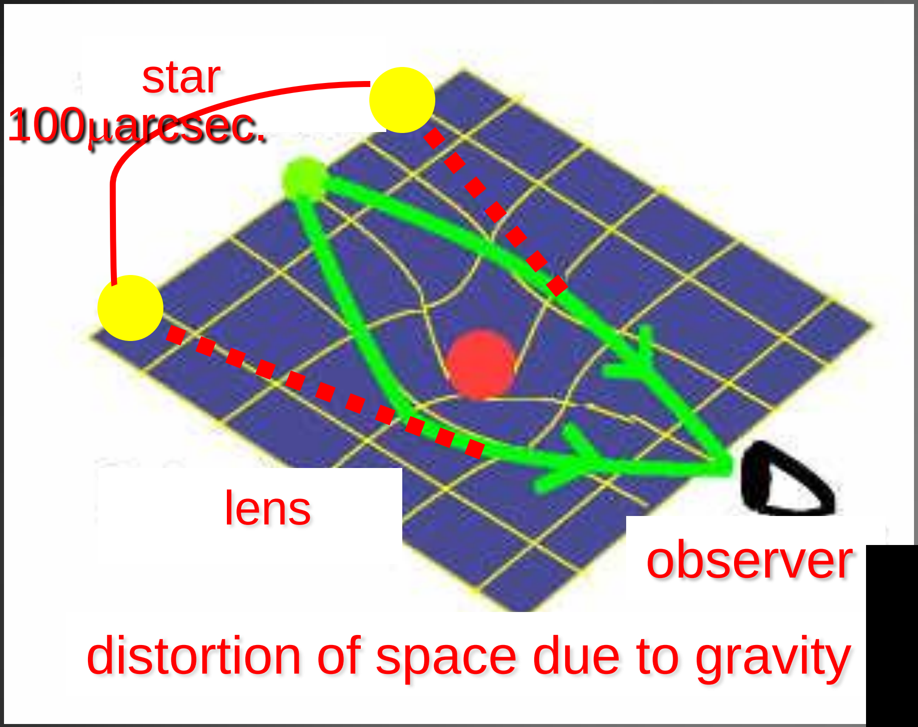
- Einstein 1936a, Science 84, 50 predicted that foreground star's gravity can magnify the apparent brightness from the background star when they perfectly aligned.

"there is no great chance of observing this phenomenon."

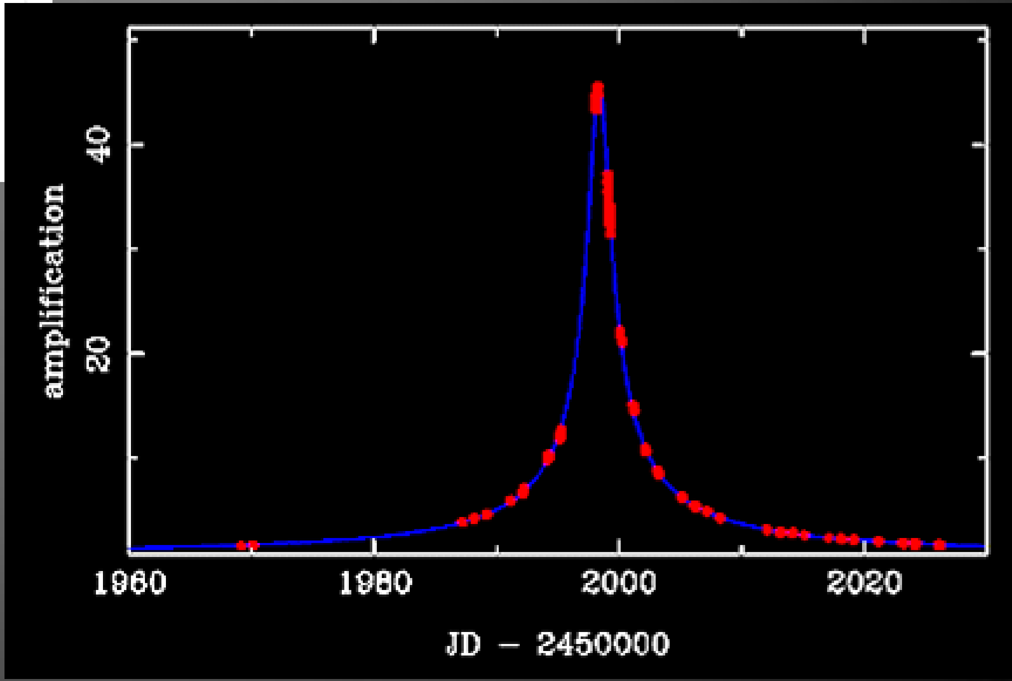
- Einstein 1936b (private letter to Science editor)

"Let me also thank you for your cooperation with the little publication, which Mister Mandl squeezed out of me. It is of little value, but it makes the poor guy happy."

Gravitational Microlensing

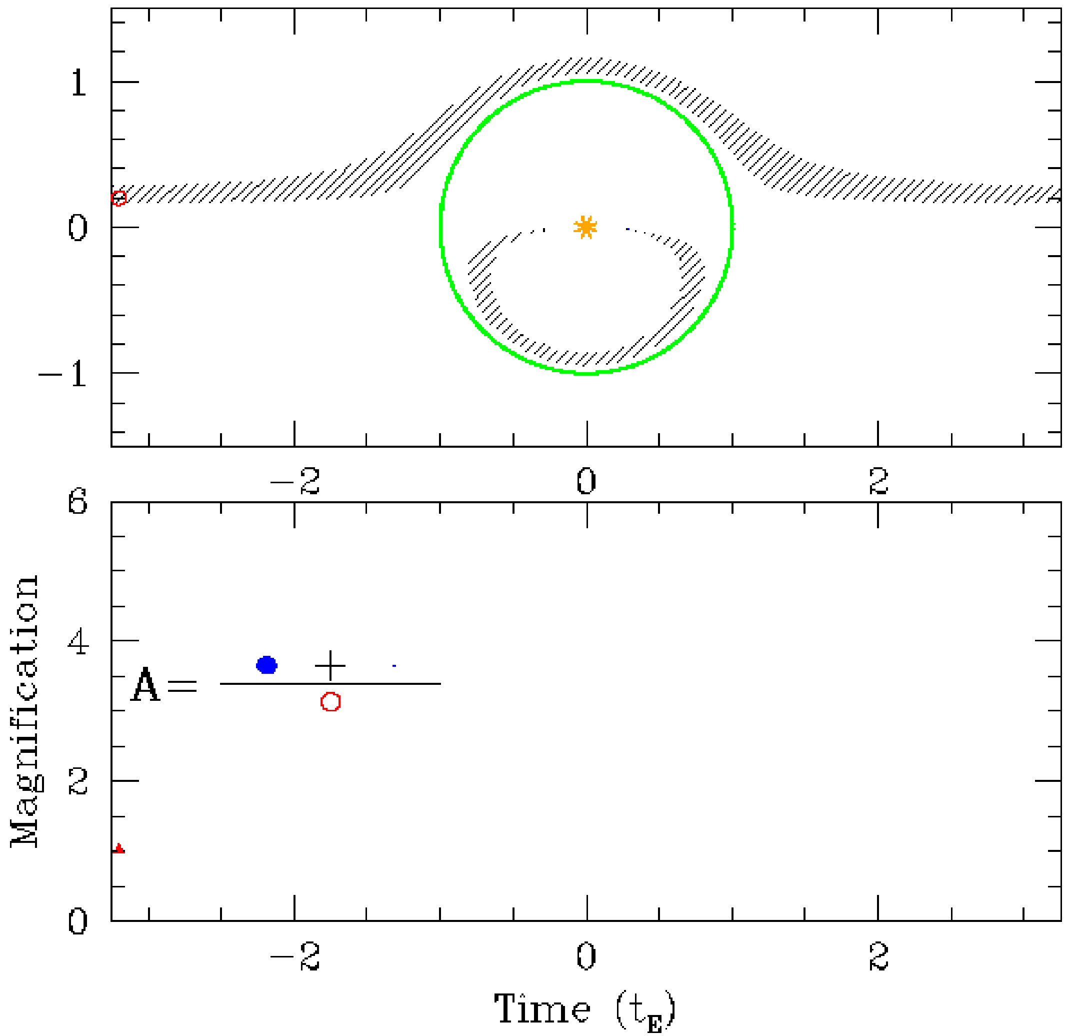


- If a lens is a star, elongation of images is an order of 100μarcsec.
- Just see a star magnified

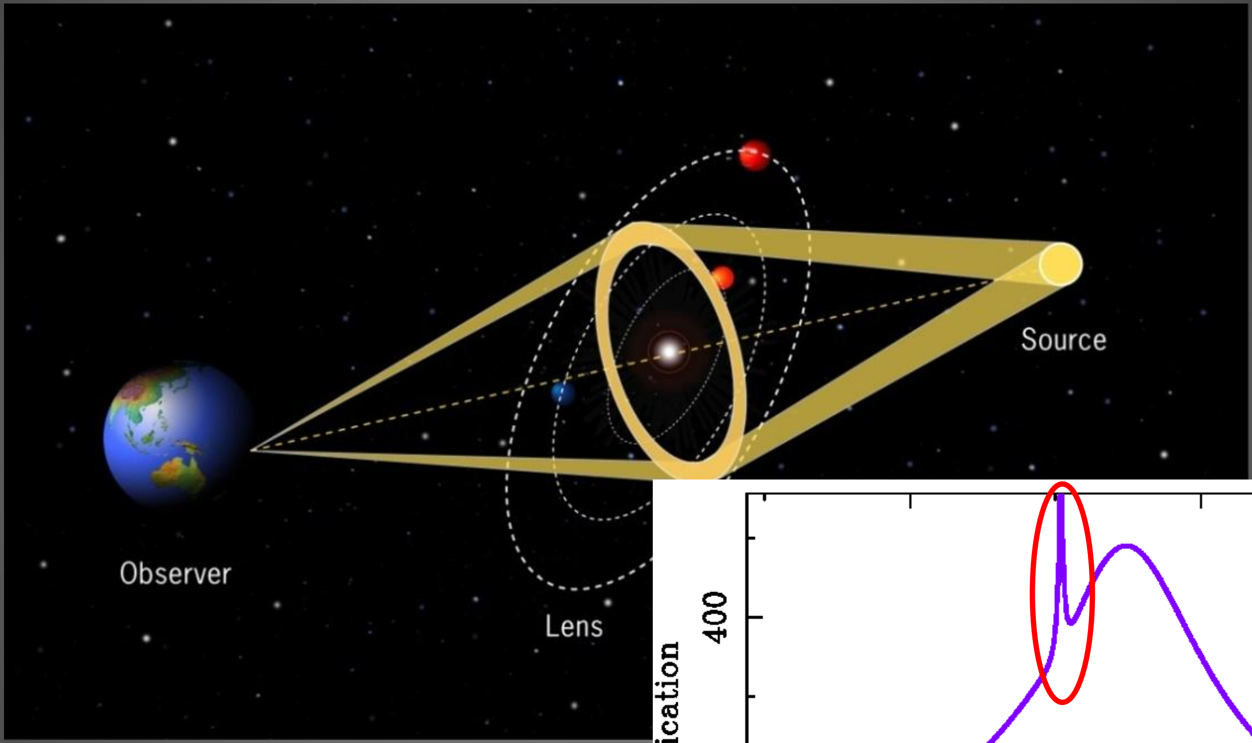


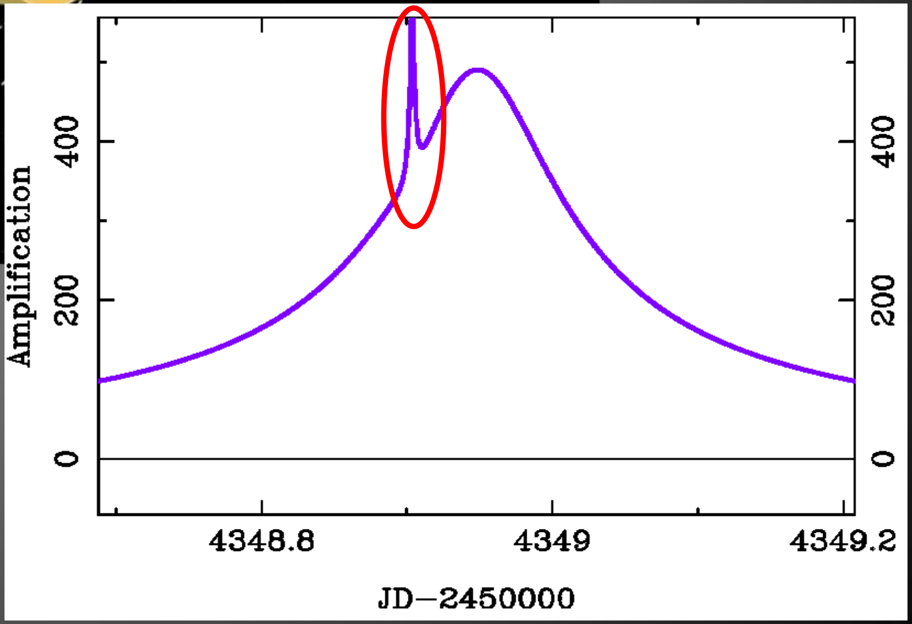
Plastic lens

Single lens



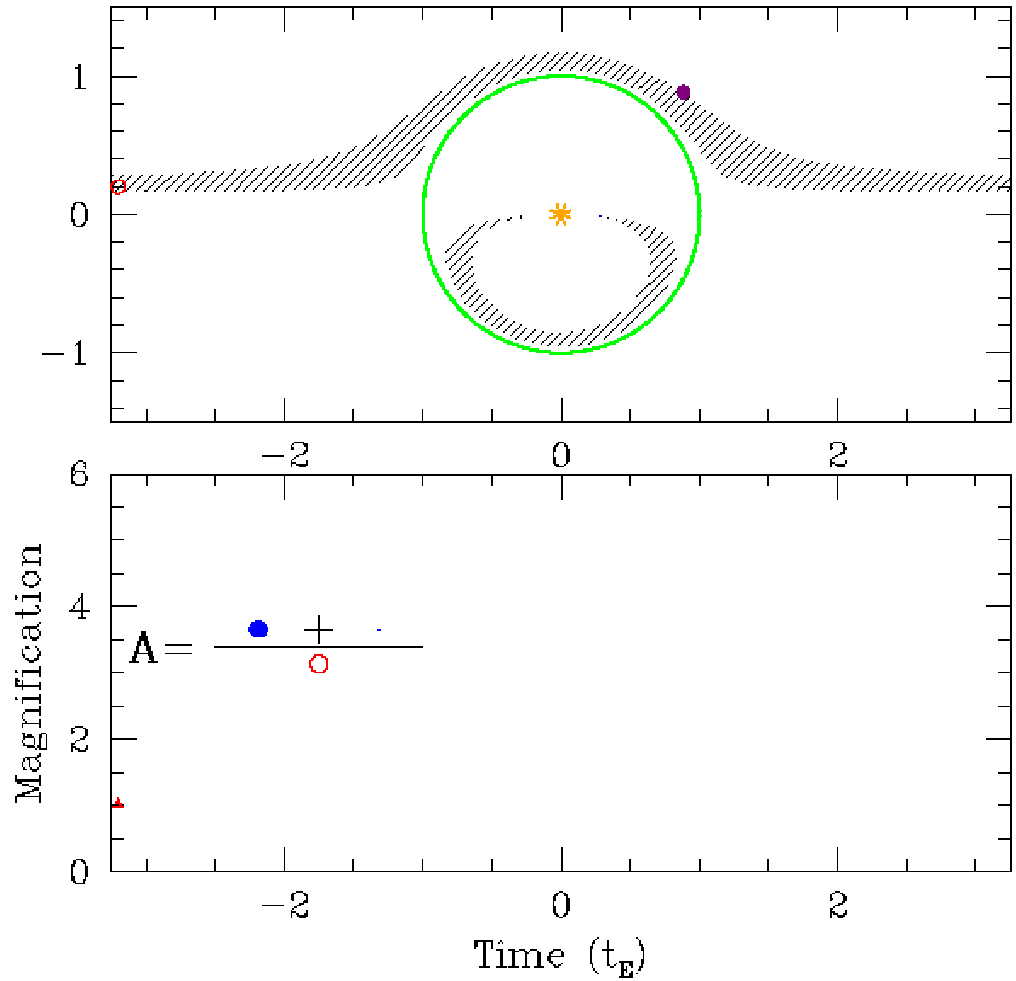
planetary microlensing





Plastic binary lens

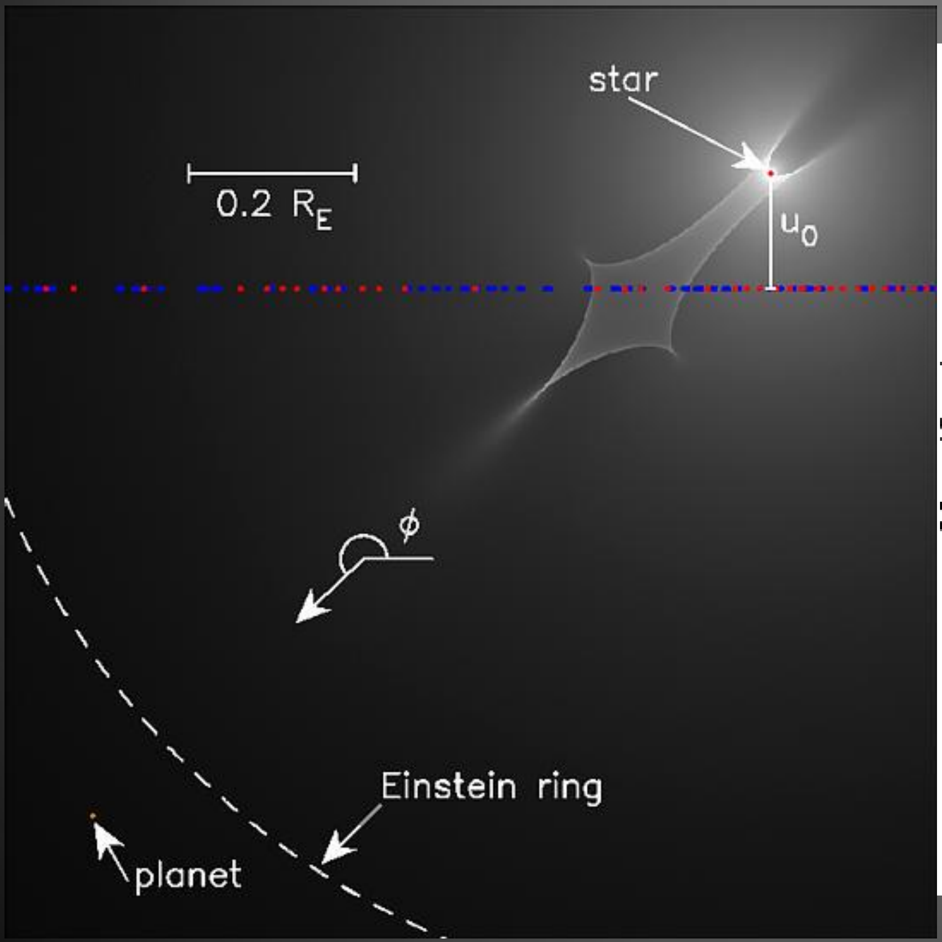
Planetary lens



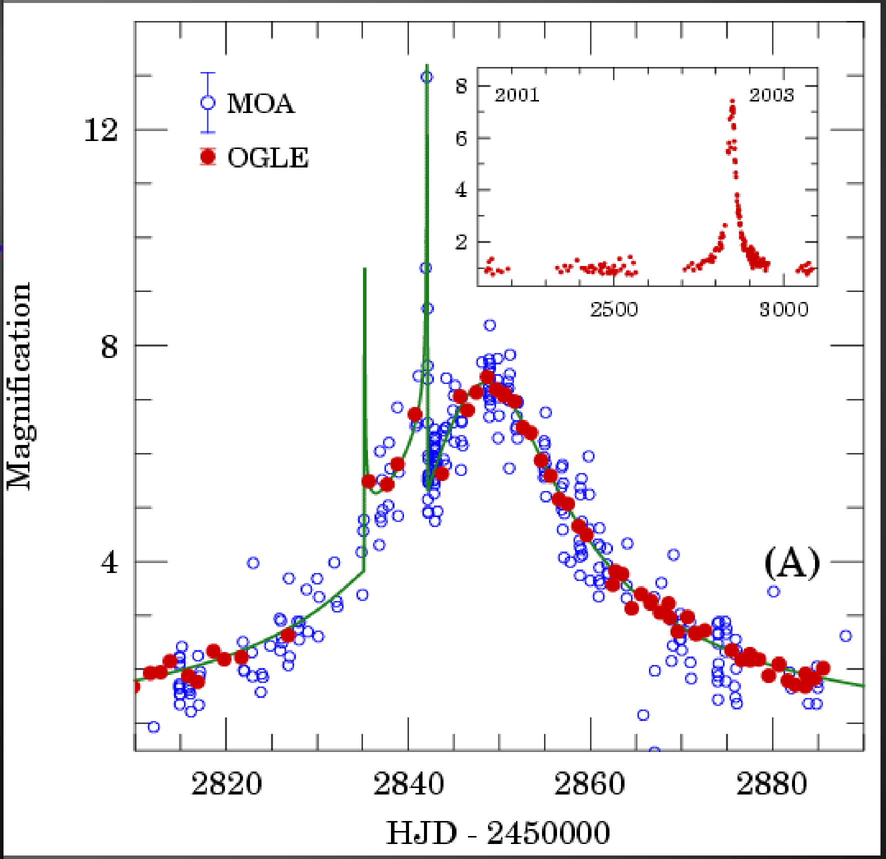
The first planet via microlensing

OGLE 2003-BLG-235/MOA 2003-BLG-53

Magnification map

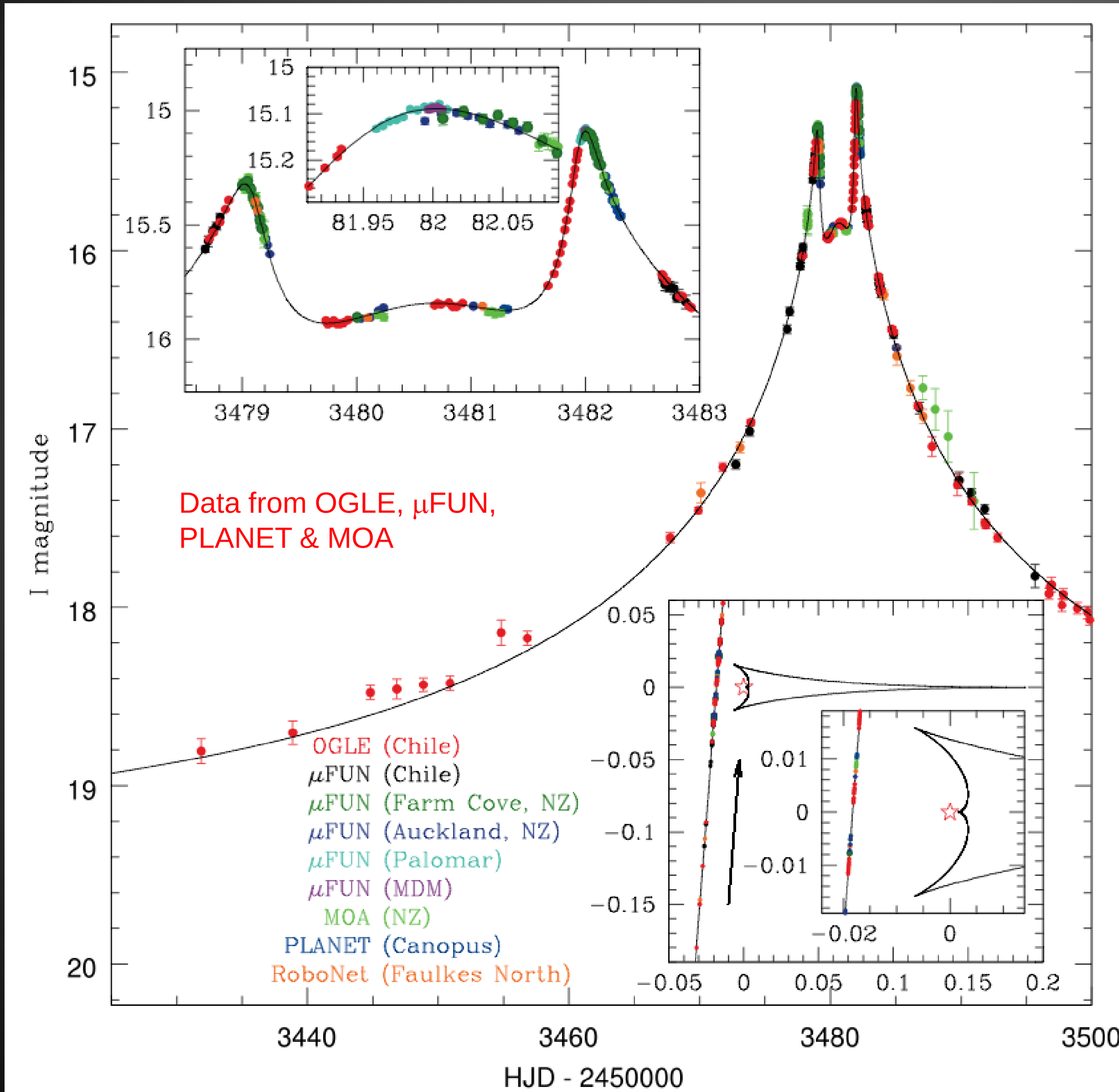


Mass : ~M_J, Sep. : ~3AU



2^{nd} Exoplanet Discovery by μlensing

OGLE 2005-BLG-71
(Udalski, et. al.2006
Dong et al. 2008)

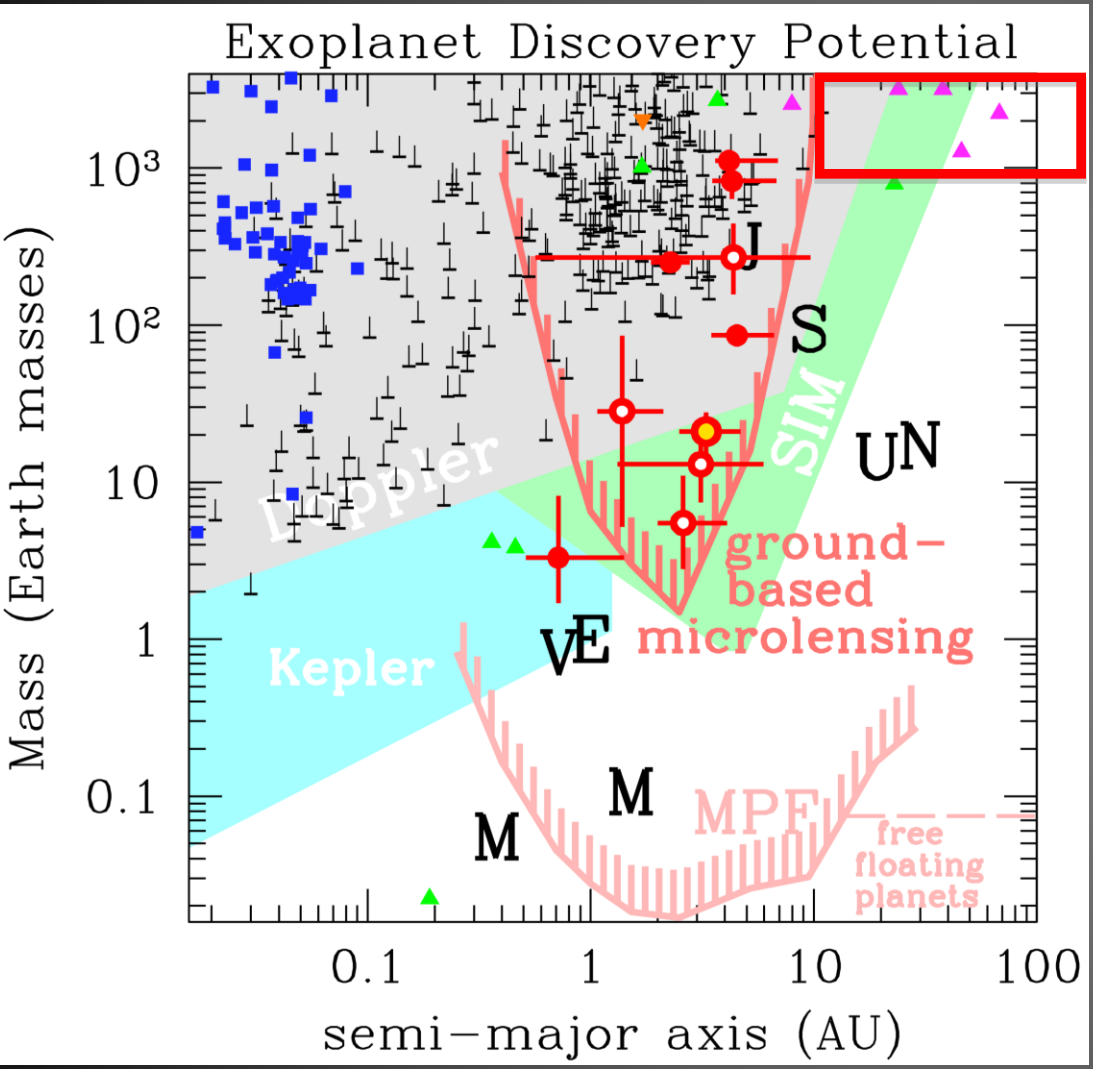


- M_L=0.46±0.04$M_\odot$
- D_L=3.3±0.4kpc
- M_p=3.5±0.3M_J
- Sep=3.6±0.2AU
- V~103km/s (HST)

The most massive Planet at wide sep for M-dwarf
Challenging to form in core-accretion model

Thick disk

Sensitivity of various methods



- •RV
- •transit
- •Direct image
- •Microlensing :
  not rely on flux from host

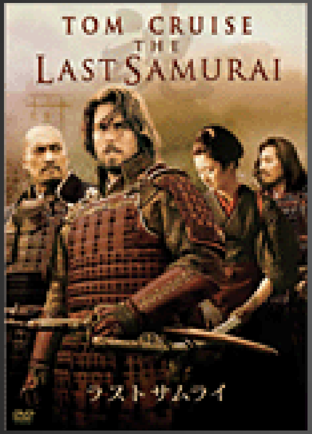
- •1-6 AU : beyond snow line
- •small planet : down to Earth
- •Faint star :M-dwarf, brown dwarf
- •No host : free floating planet
- •Far system: galactic distribution

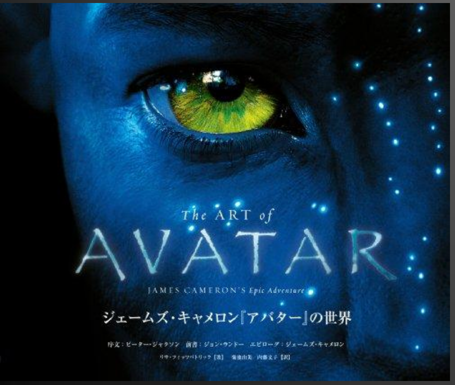
MOA (since 1995)

（Microlensing Observation in Astrophysics）

（New Zealand/Mt. John Observatory, Latitude： 44°S, Alt: 1029m）

New Zealand


TOM CRUISE
THE
LAST SAMURAI
ラストサムライ

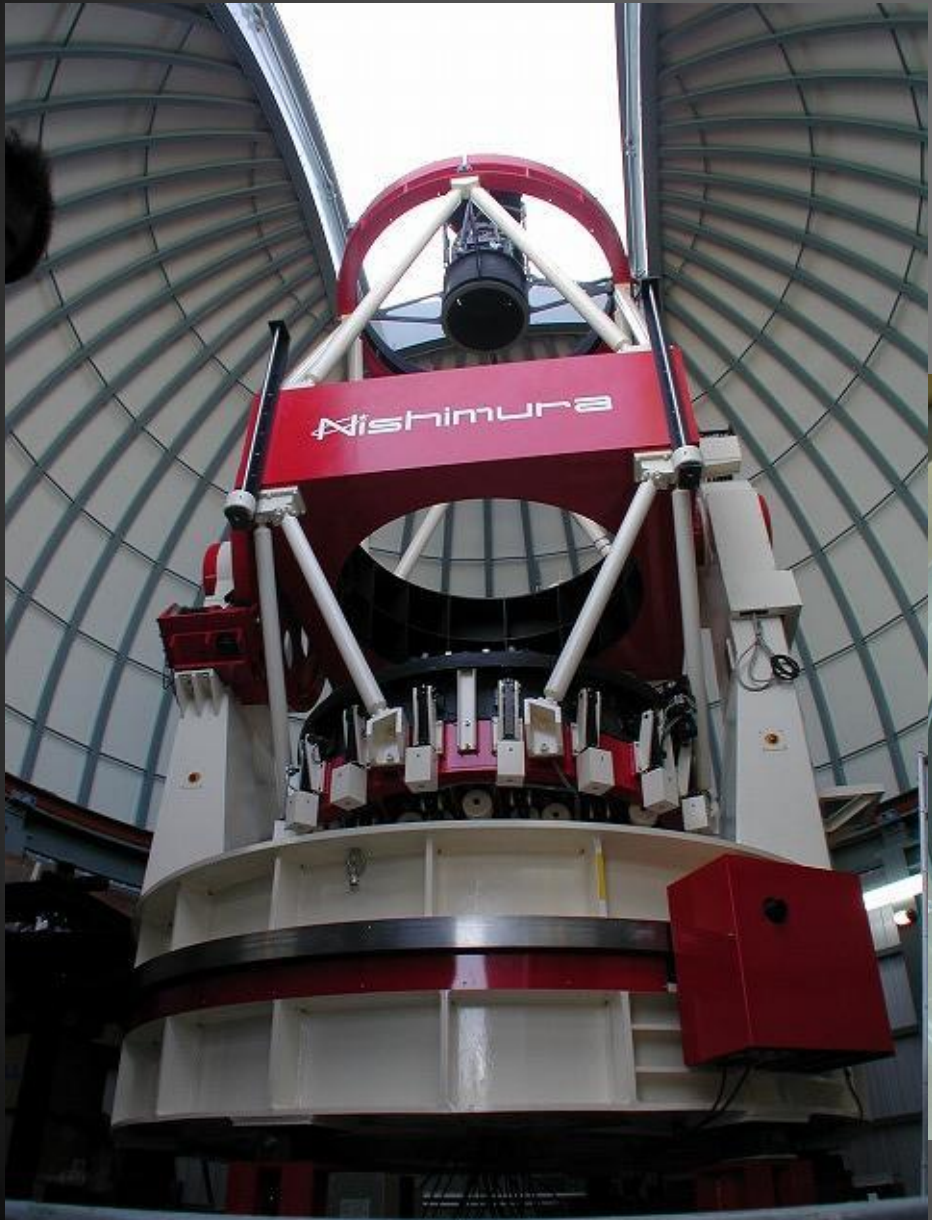

The ART of
AVATAR
JAMES CAMERON'S Epic Adventure
ジェームズ・キャメロン『アバター』の世界

MOA (until ~1500)
（the world largest bird in NZ）

- height:3.5ｍ
- weight:250kg
- can not fly
- Extinct 500 years ago （Maori ate them)

MOA-II 1.8m

Mirror : 1.8m
CCD : 80M pix.(12x15cm)
FOV : 2.2 deg.^{2}
(10 times as full moon)



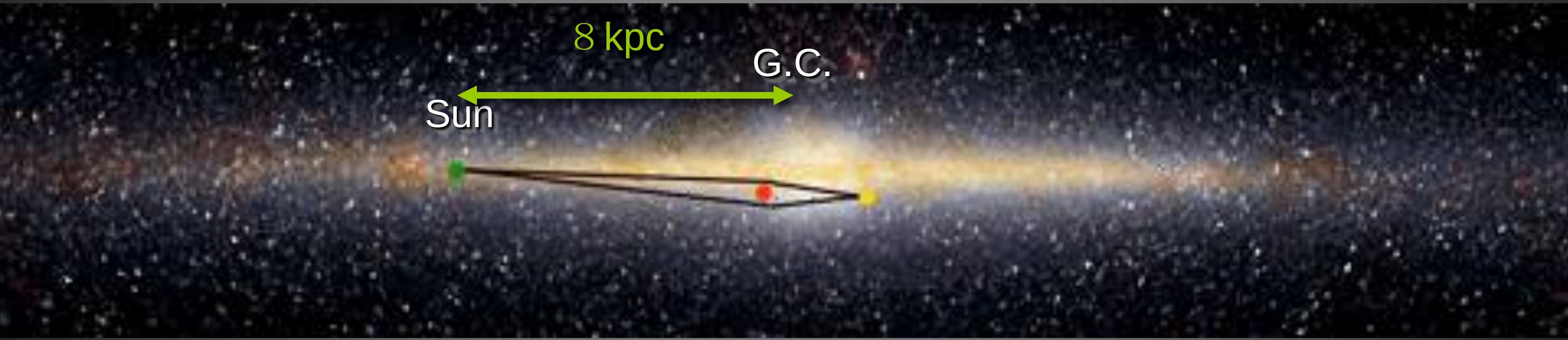
Survey towards the Galactic Bulge

☝ why ? ➔ Probability:

Microlensing : ~10^{-6} events/yr/star

Planetary event : ~10^{-2}

➔ need Wide Field for Many stars



Time scale ~ 30days ($M_{\odot}$)

~ a few days (M_{Jup})

~ hours ($M_{\oplus}$)

➔ need high cadence

Microlensing observation global network

Survey Group

MOA(NewZealand)

OGLE(Chile),

- Wide field
- Low cadence

Micro lensing Alert →

Anomaly Alert ← →

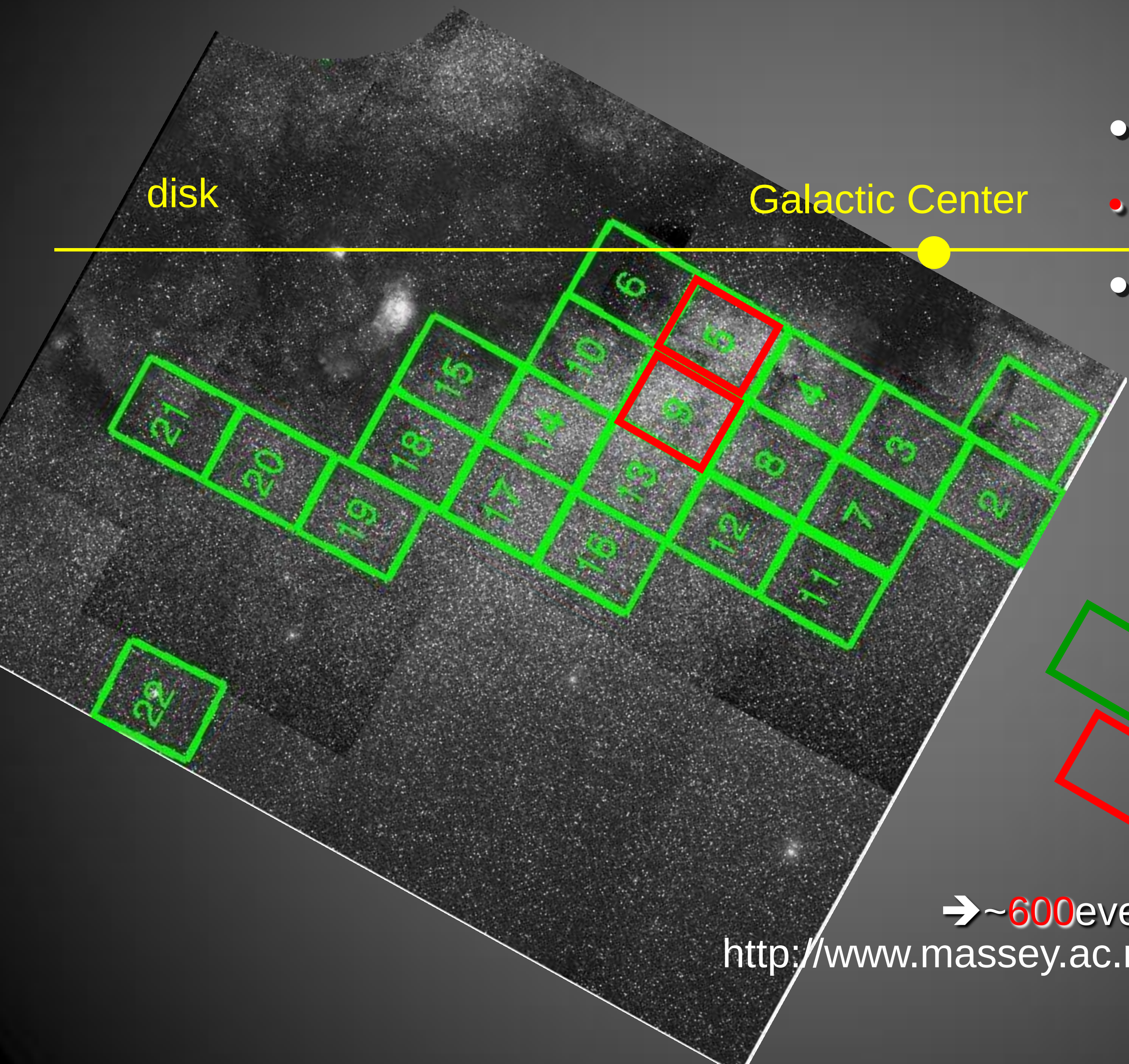
Follow-up Group

PLANET
μFUN
Robonet-II
MiNDSTEp

- Pointing each candidate
  High cadence

Observational fields

- 50 deg.^{2}
- （２００x full moon）
- ５0 Mstars



1obs/１hr

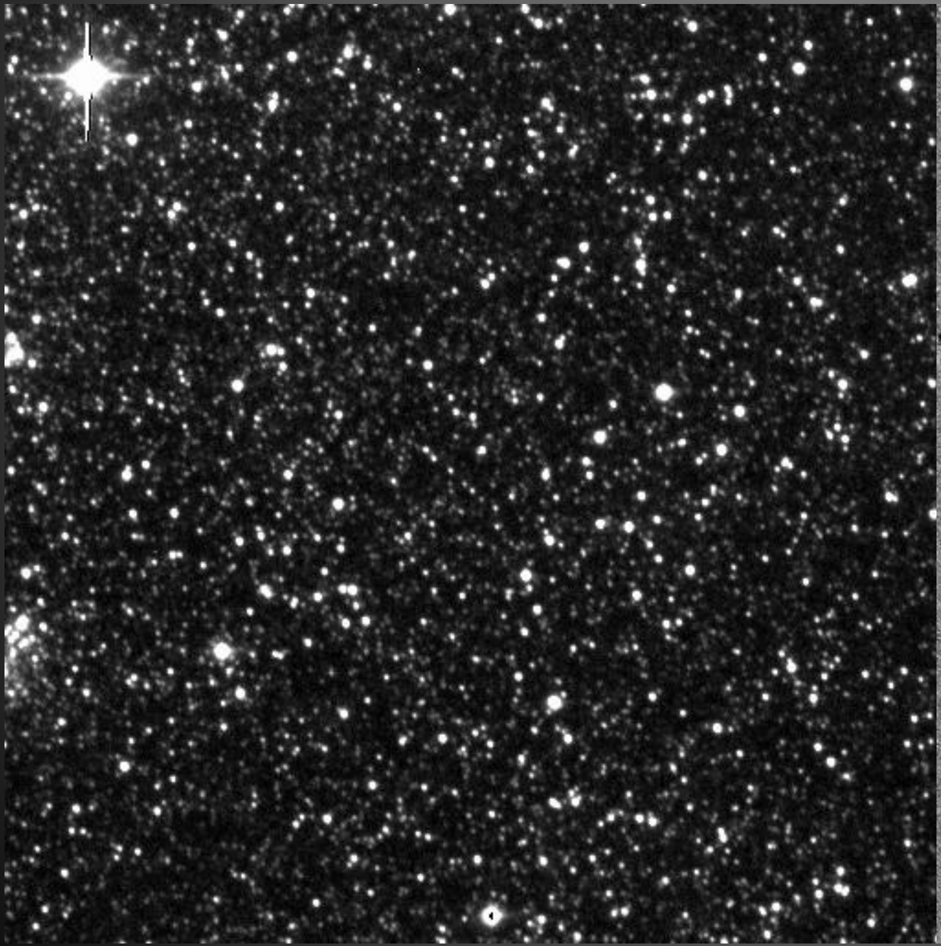
1obs/１０min

→~600events／yr

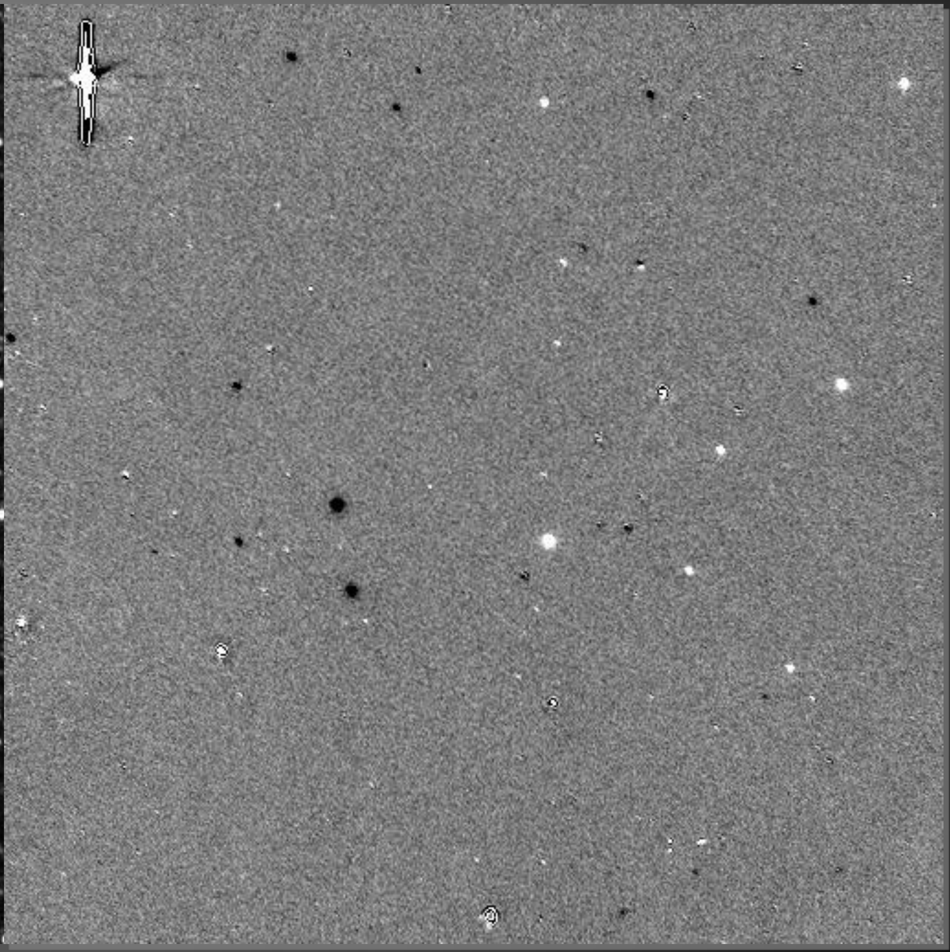
http://www.massey.ac.nz/~iabond/alert/alert.html

Difference Image Analysis (DIA)

Observed

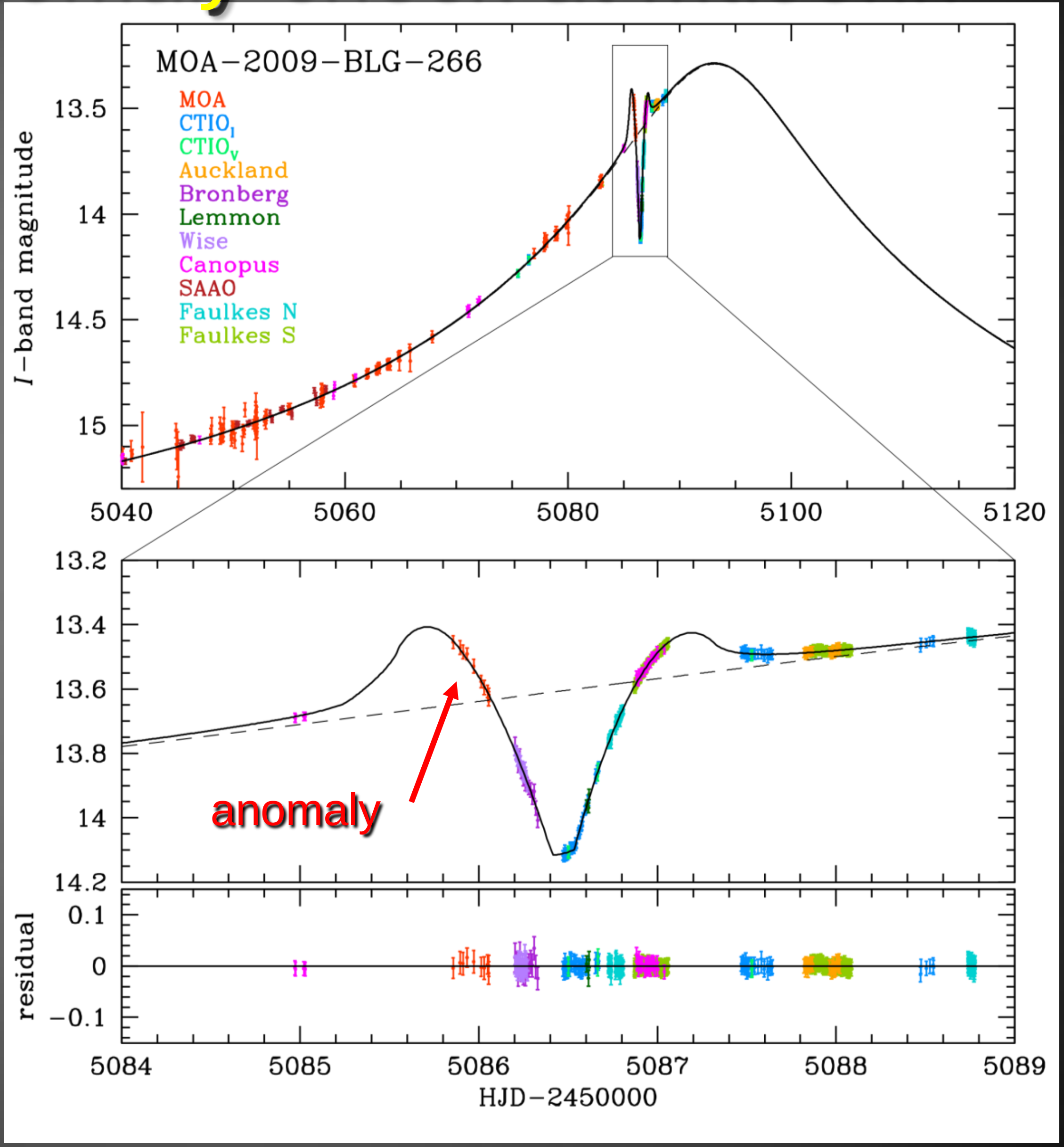


subtracted



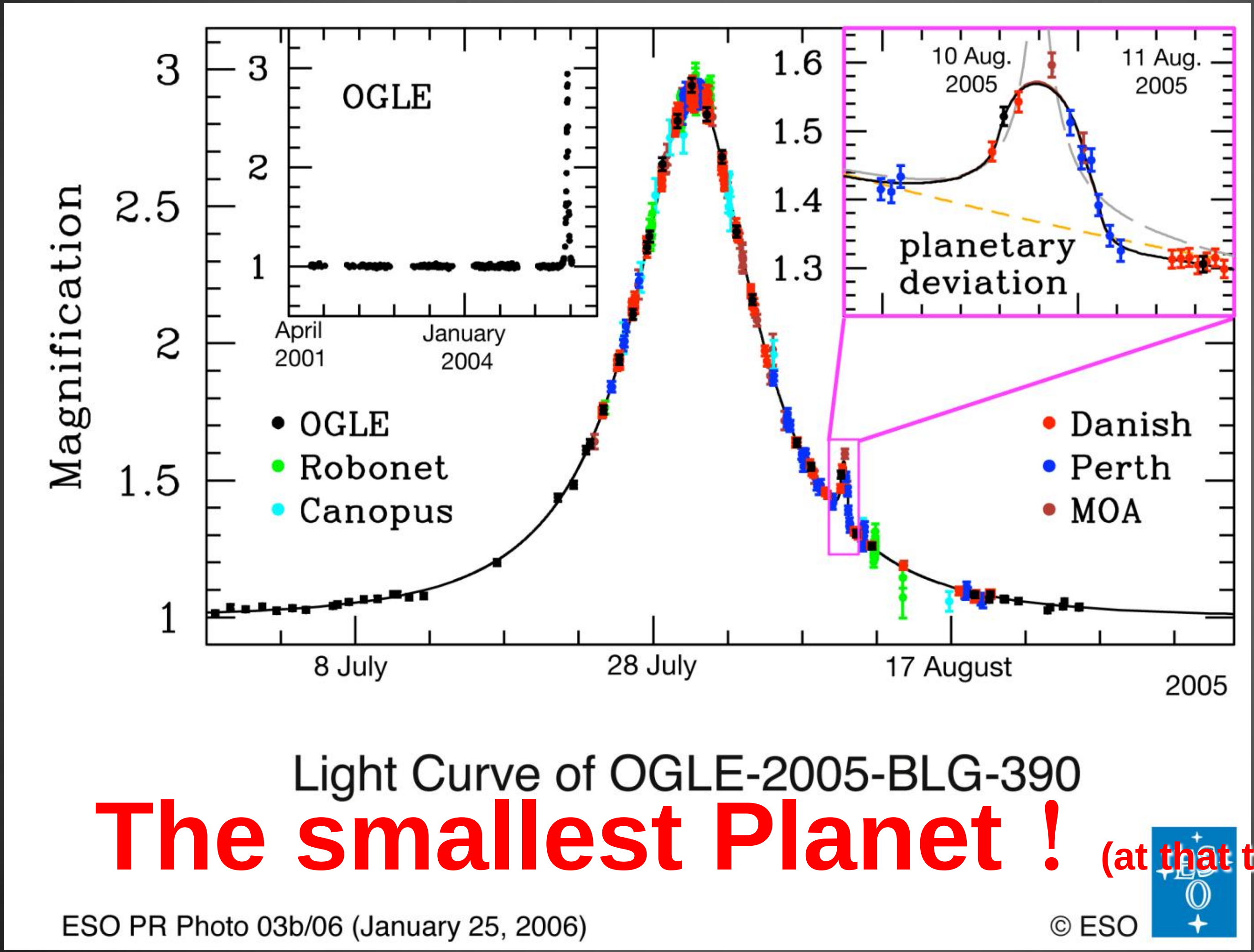
Real-time Anomaly check at Mt.John

The planet found on 11/9/2009



5.5 Earth mass:OGLE-2005-BLG-390

Sep~3AU

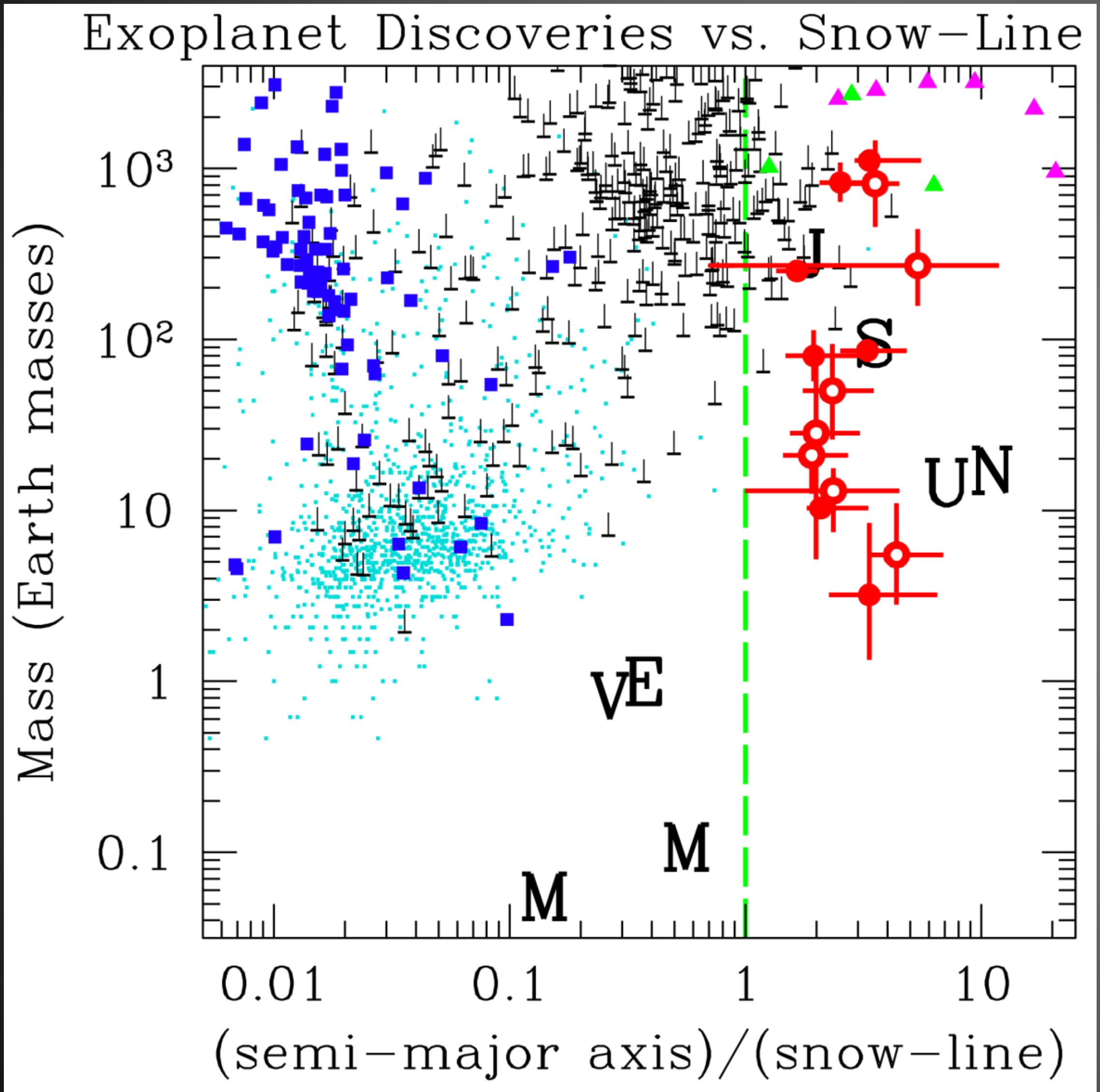


The smallest Planet ! (at that time)

- Proved microlensing is sensitive to Super earth

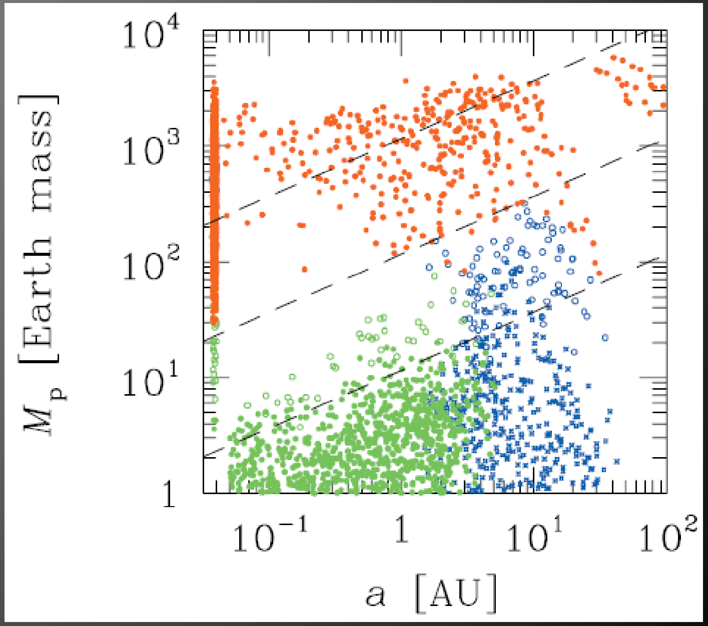
(Beaulieu et al. 2006, Nature,439,437)

Summary of Planet candidates

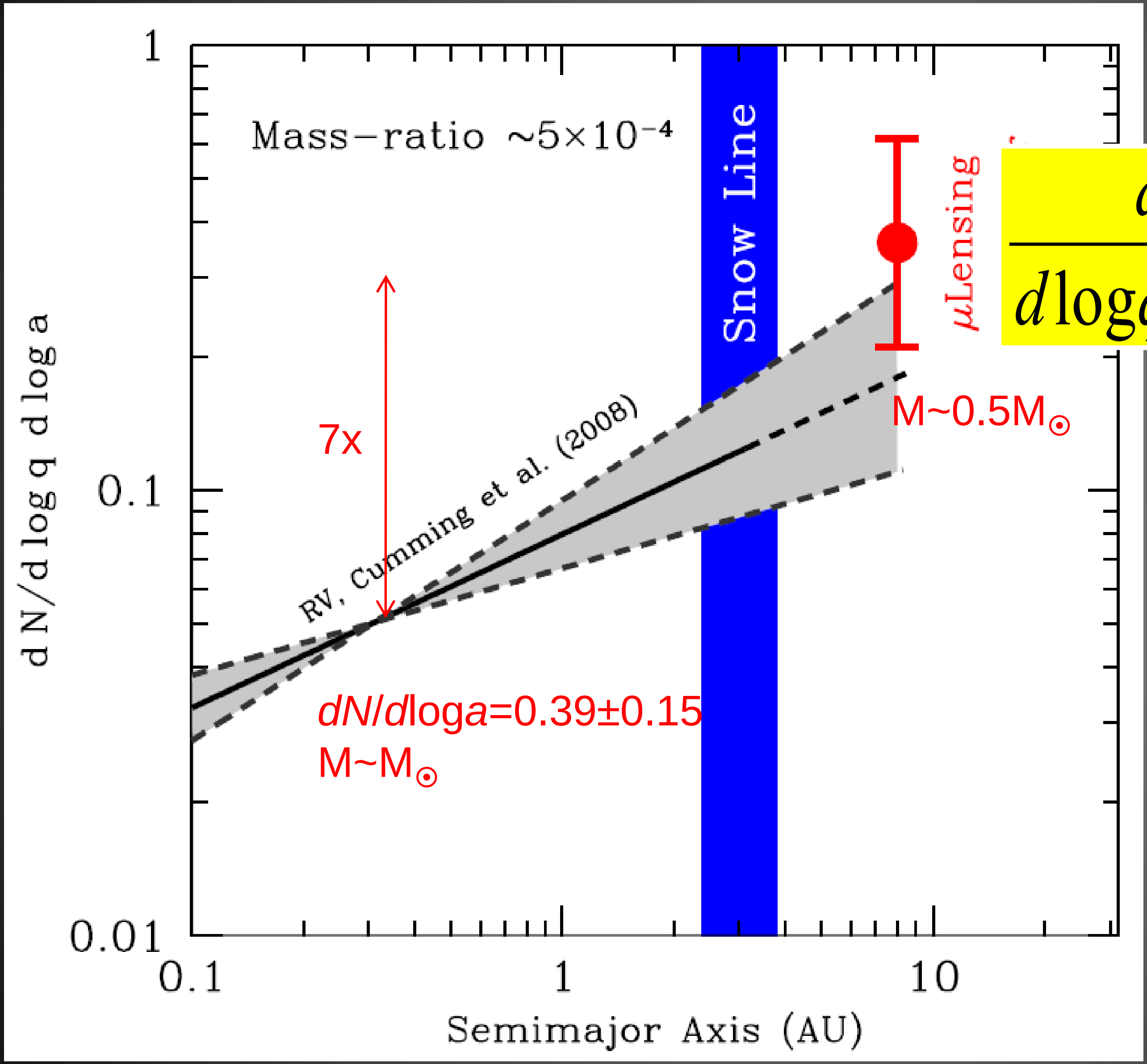


- RV
- transit
- Direct image
- Microlensing : 14planets
  - Mass measurements
  - Mass by Bayesian
- Kepler

theory. (Ida & Lin, 2004)



Planet Frequency vs semimajor axis



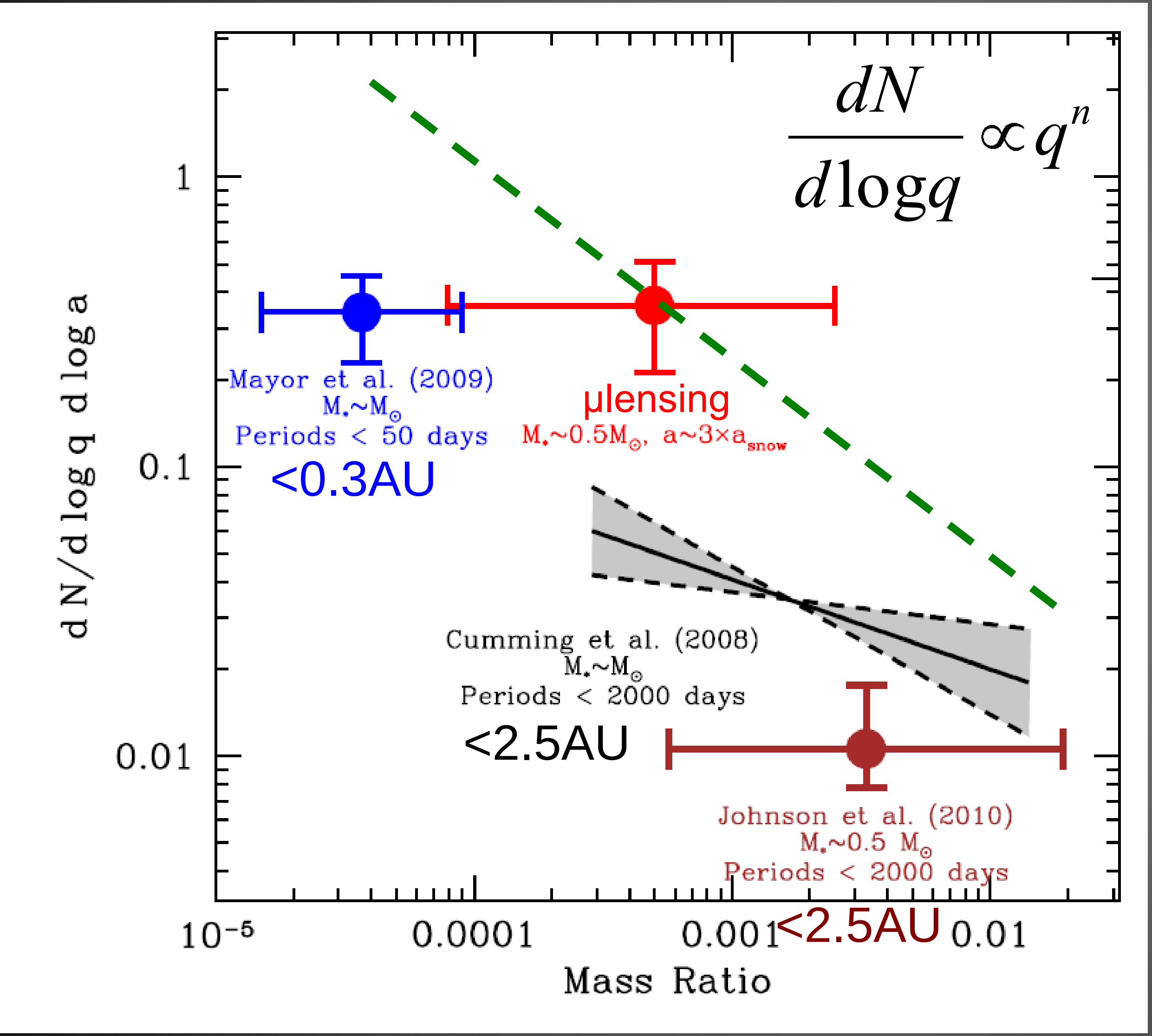
6planets

$$\frac{dN}{d\log q \, d\log s} = 0.36 \text{ dex}^{-2}$$

- Most ice & gas giant planets do not migrate very far in K,M dwarf
- Amount of migration is a continuous parameter

Gould et al. 2010

Planet mass ratio function

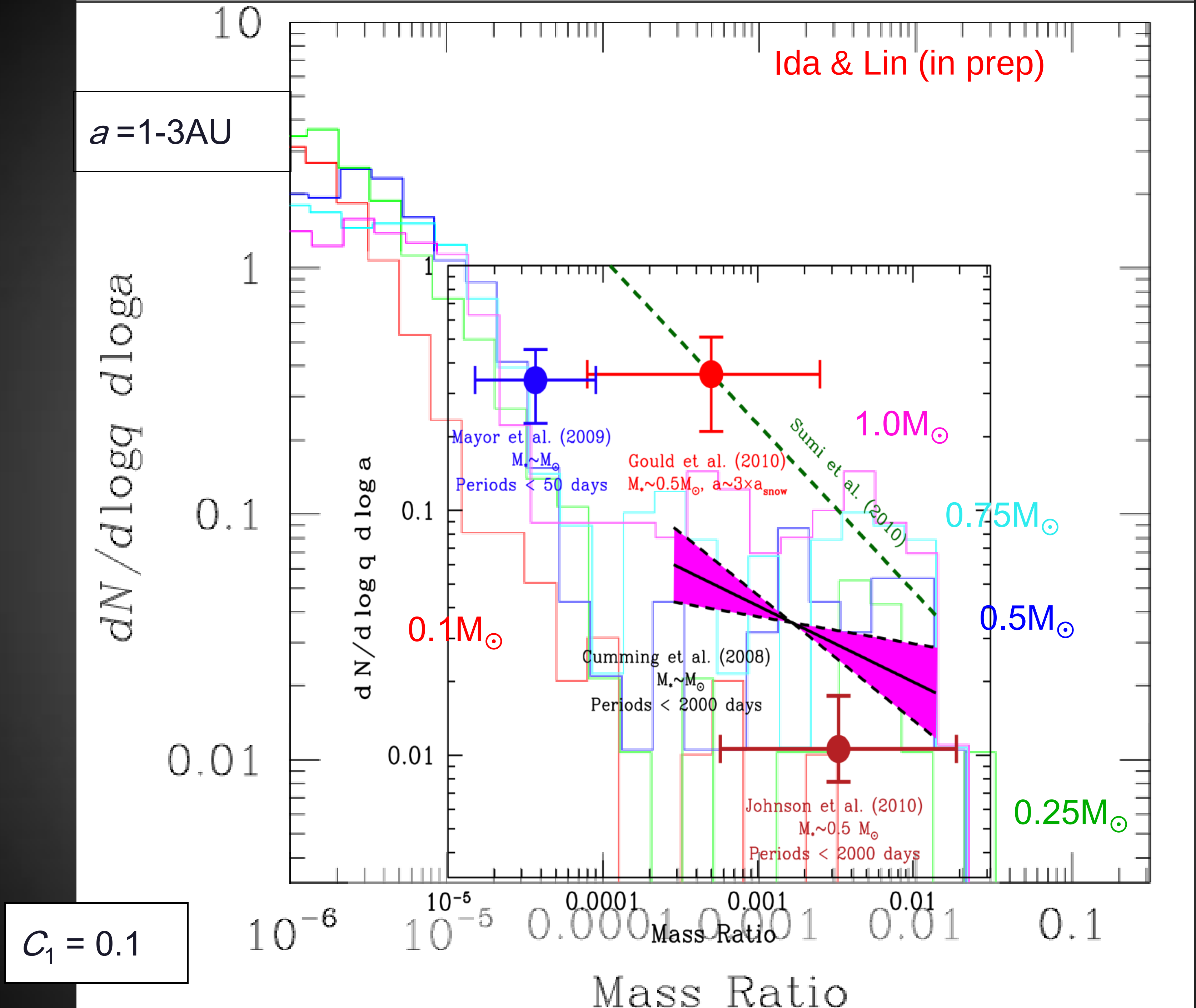


4 Neptune,
1 sub-Saturn,
5 Jupiter

$n = -0.68 \pm 0.20$ (Sumi et al. 2010)
<-0.35(95%cl)

$n = -0.31 \pm 0.20$
(RV, solar-type stars, Cumming et al. 2008)

Cold Neptunes($q \sim 5 \times 10^{-5}$) are 7^{+6}_{-3} times more common than Jupiters ($q \sim 10^{-3}$), >2.8 times (95% cl) around K,M dwarfs



Ida & Lin (in prep)
a =1-3AU
C_1 = 0.1
dN/dlogq dloga
Mass Ratio
10
1
0.1
0.01
10^{-6}
10^{-5}
0.0001
0.001
0.01
0.1
1.0M⊙
0.75M⊙
0.5M⊙
0.25M⊙
0.1M⊙
Mayor et al. (2009)
M*~M⊙
Periods < 50 days
Gould et al. (2010)
M*~0.5M⊙, a~3×a_snow
Sumi et al. (2010)
Cumming et al. (2008)
M*~M⊙
Periods < 2000 days
Johnson et al. (2010)
M*~0.5 M⊙
Periods < 2000 days
d N/d log q d log a

Summary of bound planets

- *Mass-ratio function:* $\propto q^n$: n=-0.7±0.2, n<-0.35(95%cl) (>snow line)
  - Cold Neptune are 7x common or at least 3x more common than Jupiters in K,M-dwarf
- Frequency: $dN/(d\log q\, d\log s)$=0.36dex^{-2}
  - 7x more than at a=0.3AU by RV (Consistent with slope in sep)
  - Most giant planets do not migrate very far
  - Amount of migration is a continuous parameter
  - 10x more than core accretion model.
  - 1.2 exoplanets per star at 0.03-10 AU! (RV+Microlenisng)

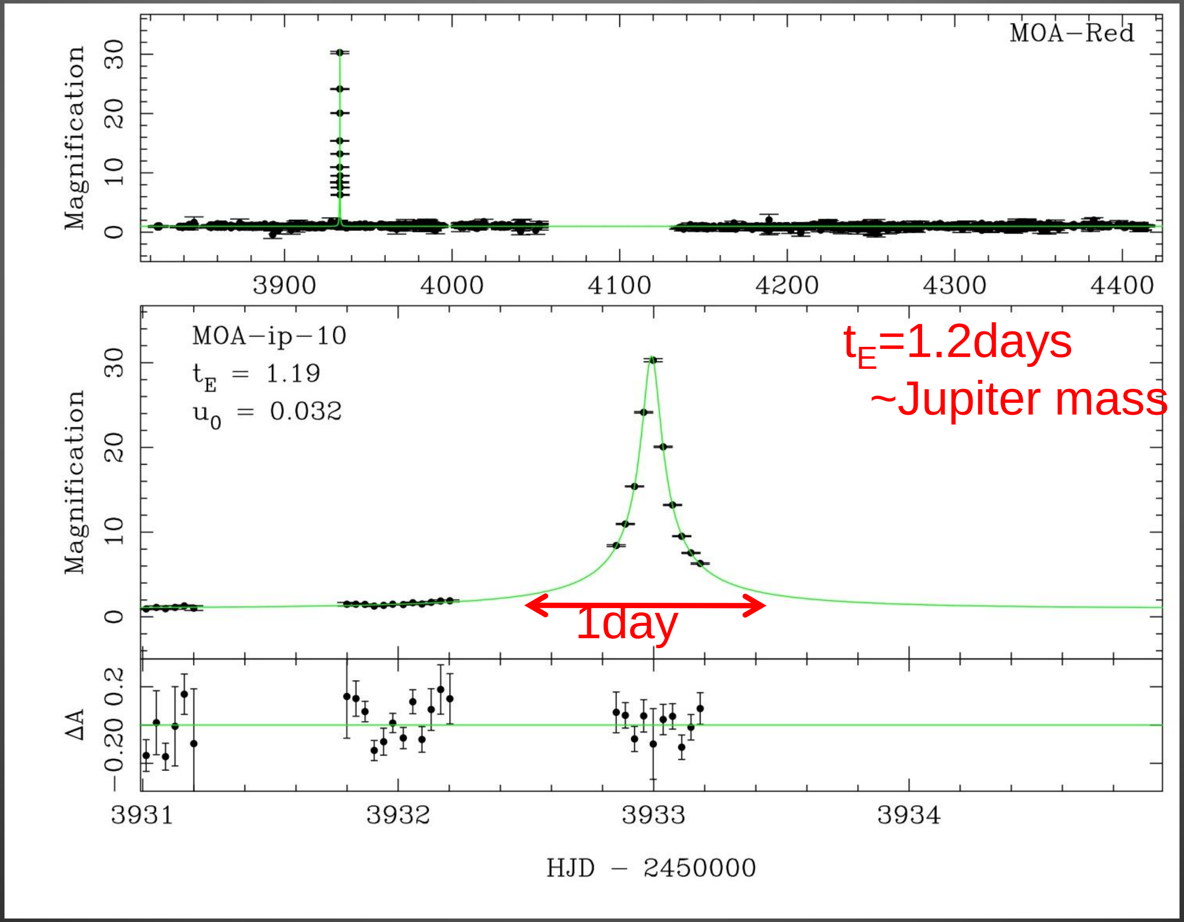
10 events with timescale $t_E < 2$ days

474 events in 2 years

timescale : $t_E = \frac{R_E(M,D)}{v_t} \sim \sqrt{M/M_J}\ day$

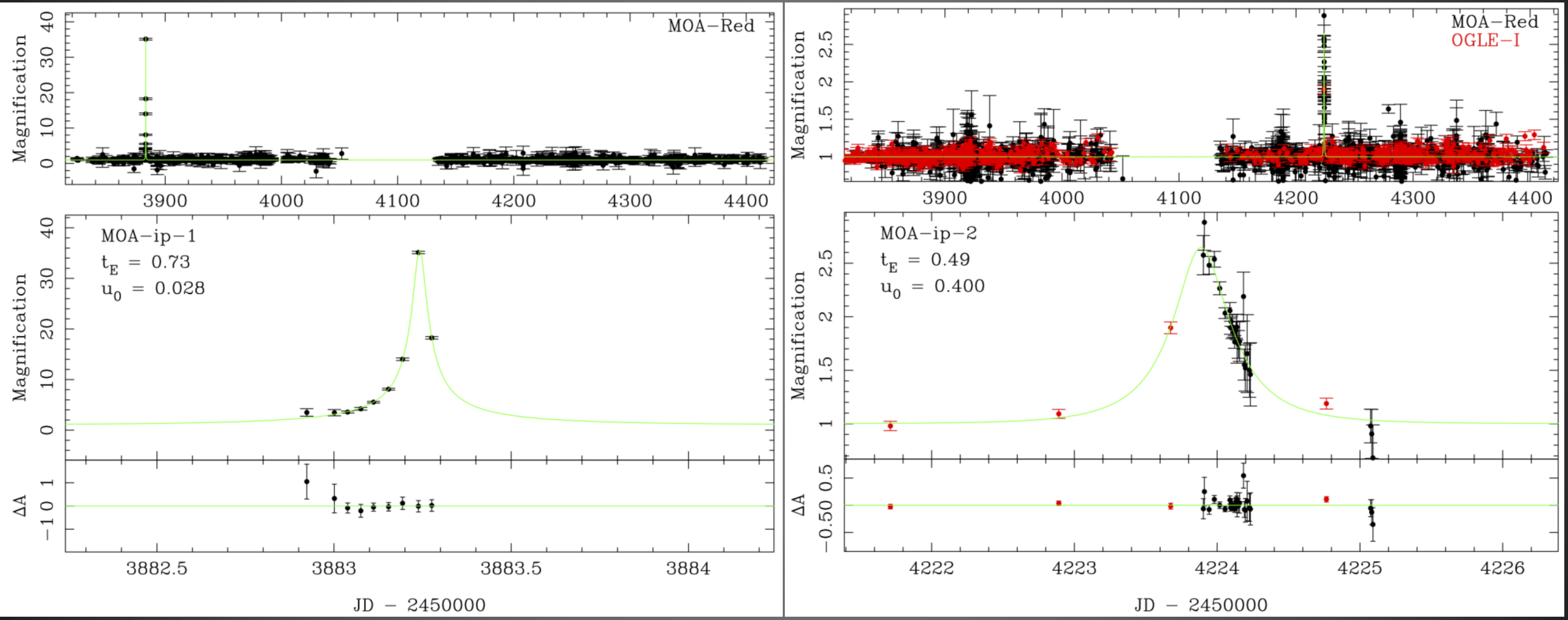
~20 days for stars

M : lens mass
M_J: Jupiter mass
D : distance
v_t: velocity



10 events with t_E< 2 days from 2006-2007

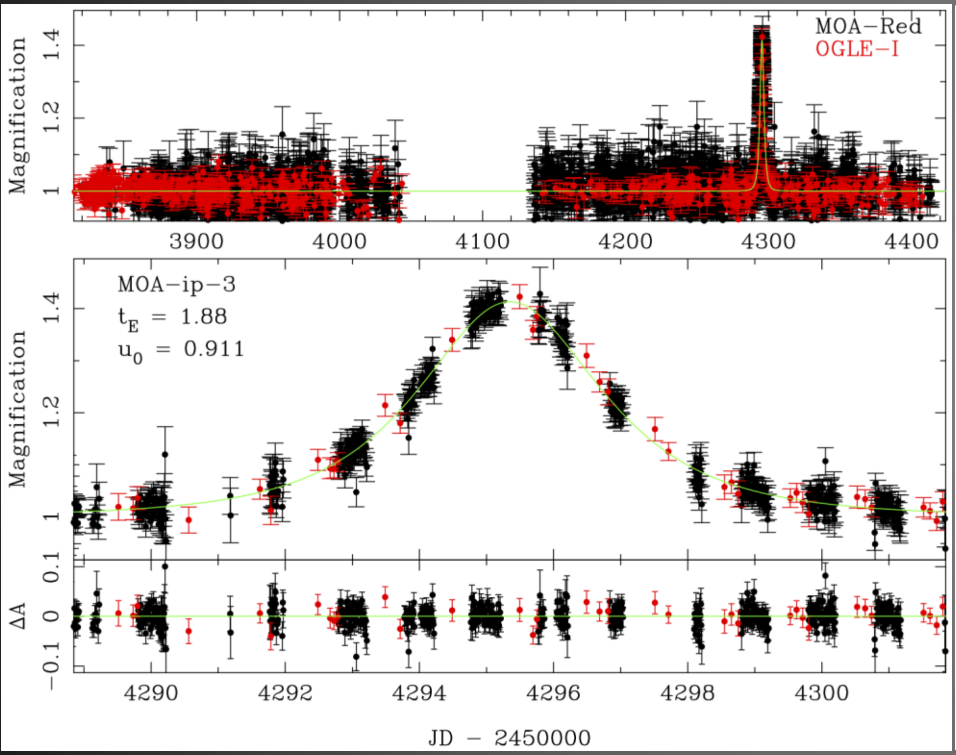
(events 1, 2)

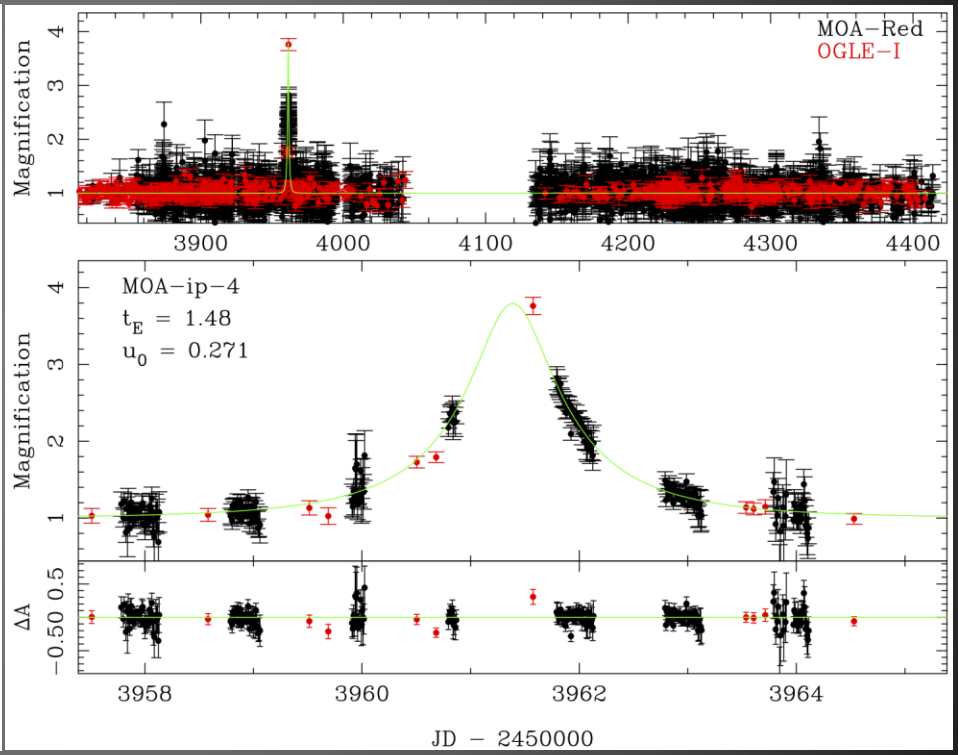


MOA data in black, confirmed by OGLE data in red

10 events with t_E< 2 days from 2006-2007

(events 3, 4)

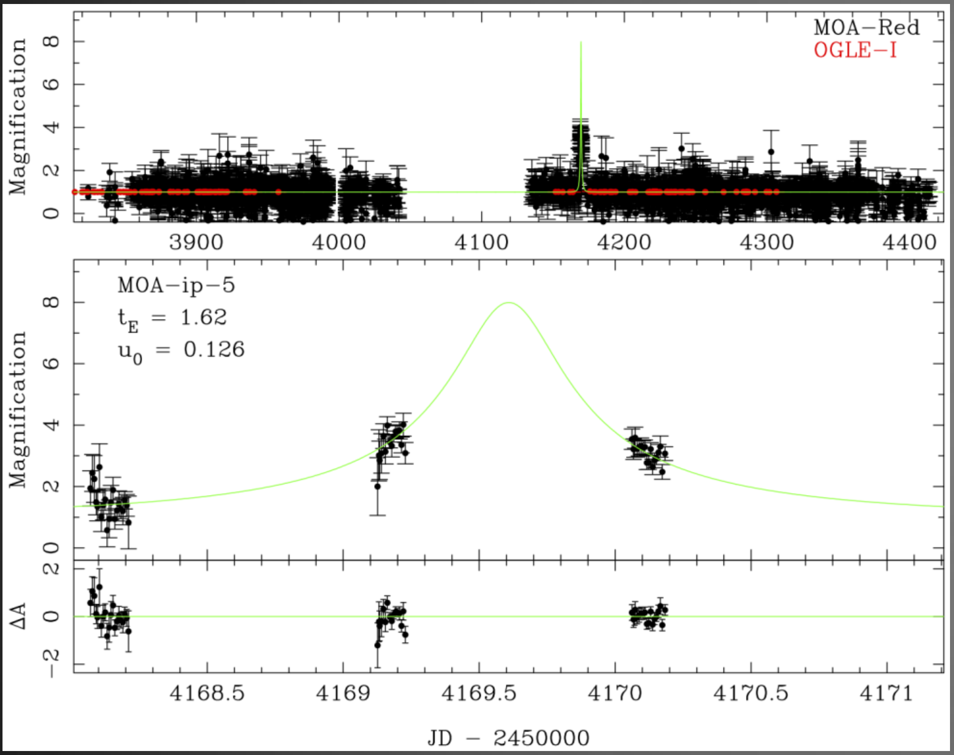


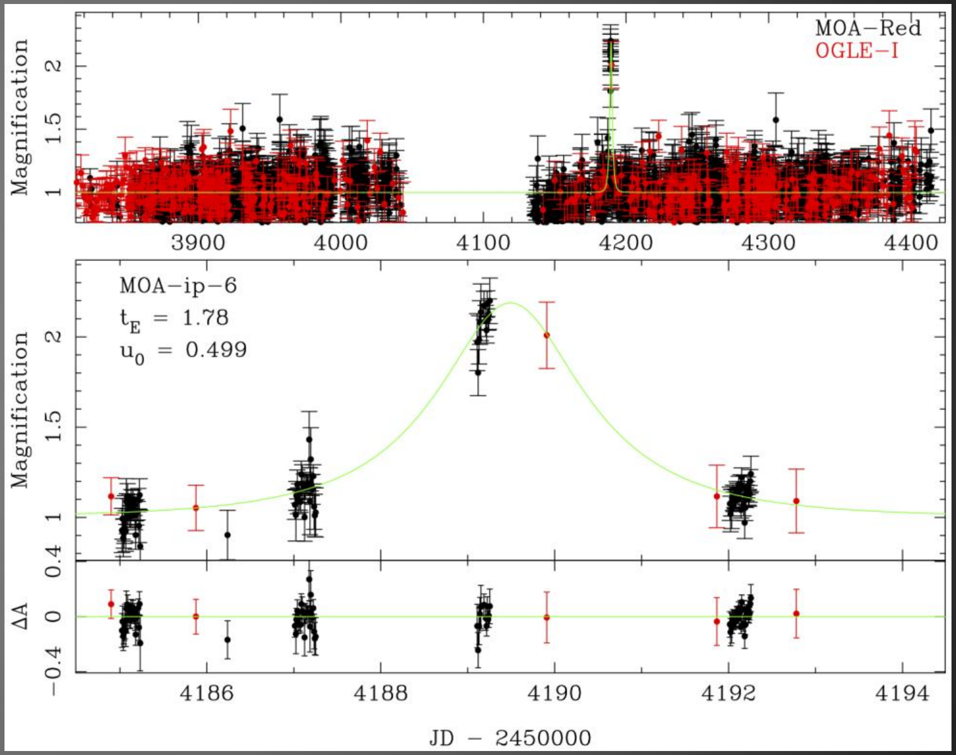


MOA data in black, confirmed by OGLE data in red

10 events with t_E< 2 days from 2006-2007

(events 5, 6)

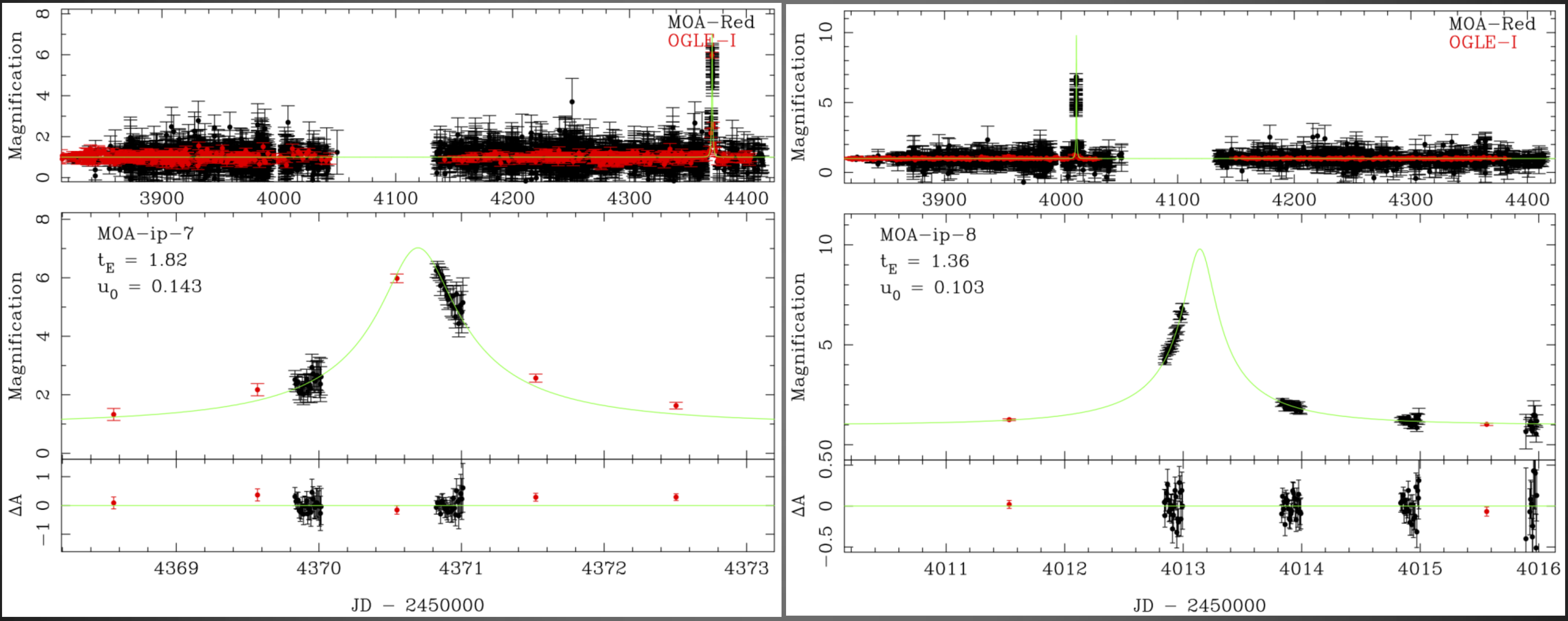




MOA data in black, confirmed by OGLE data in red

10 events with t_E< 2 days from 2006-2007

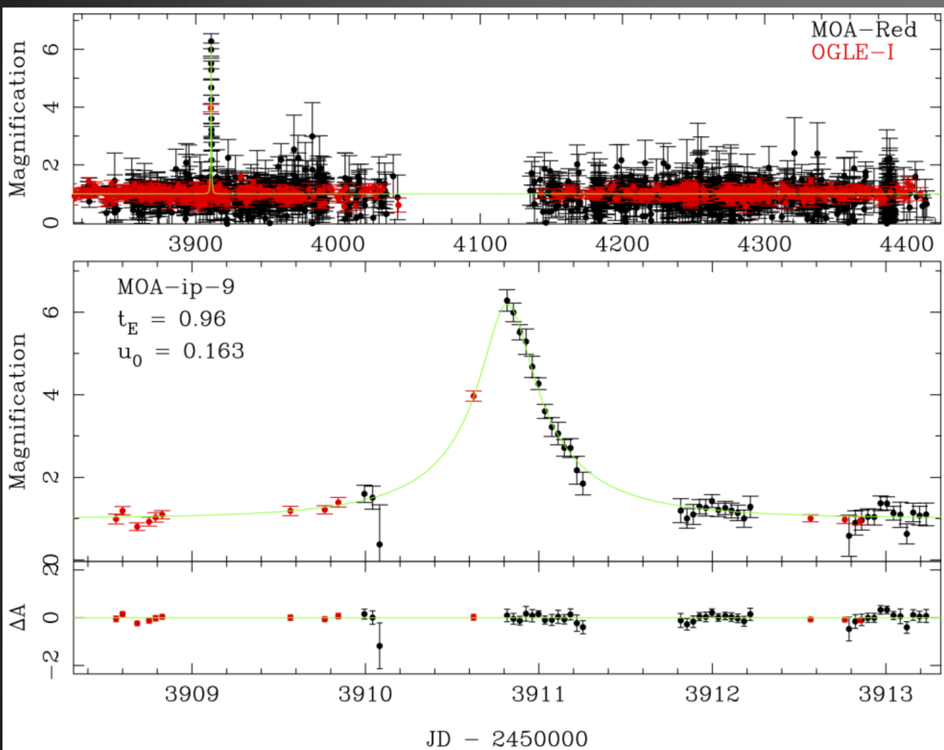
(events 7, 8)

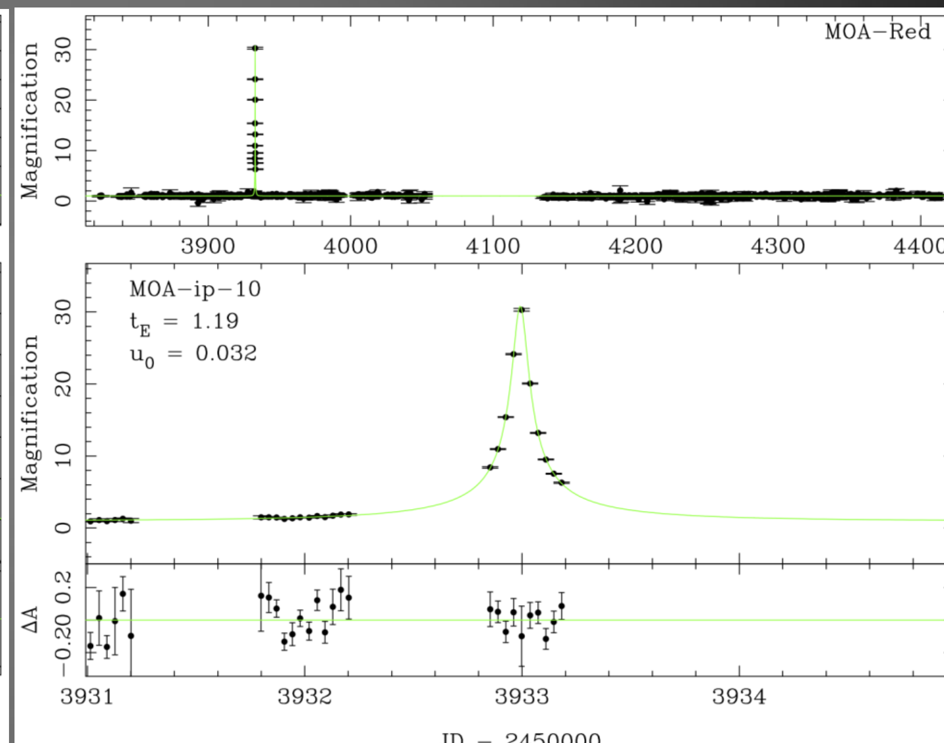


MOA data in black, confirmed by OGLE data in red

10 events with t_E< 2 days from 2006-2007

(events 9,10)





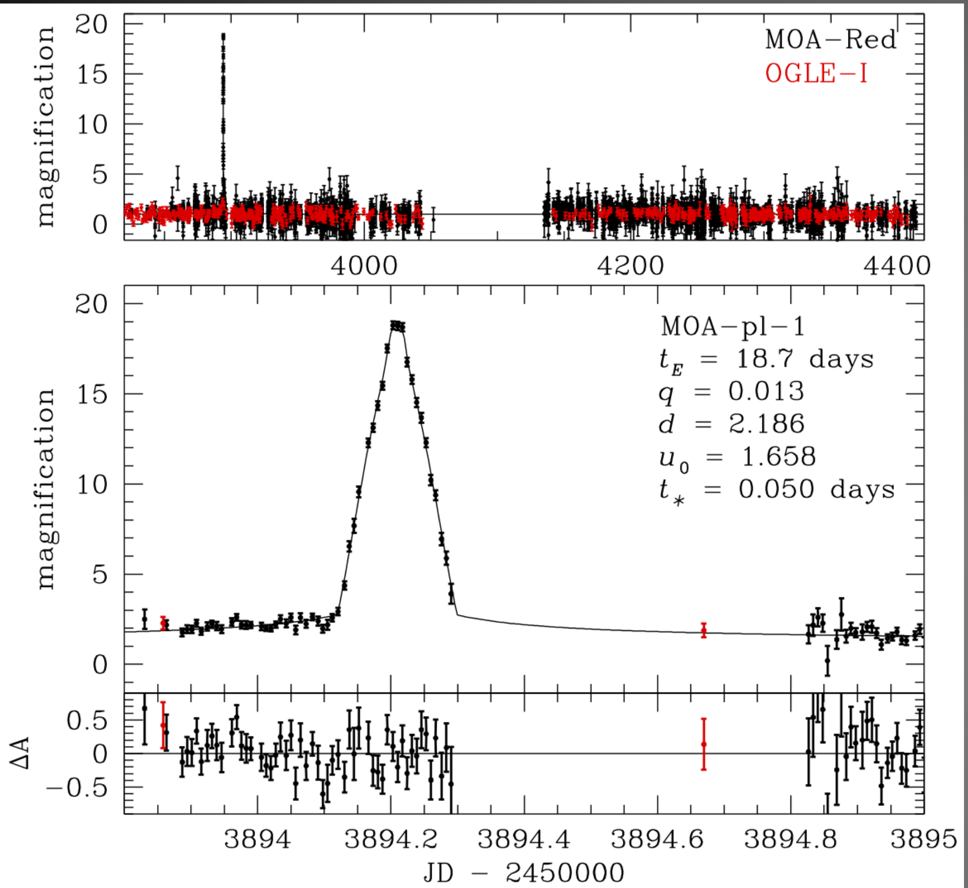
MOA data in black, confirmed by OGLE data in red

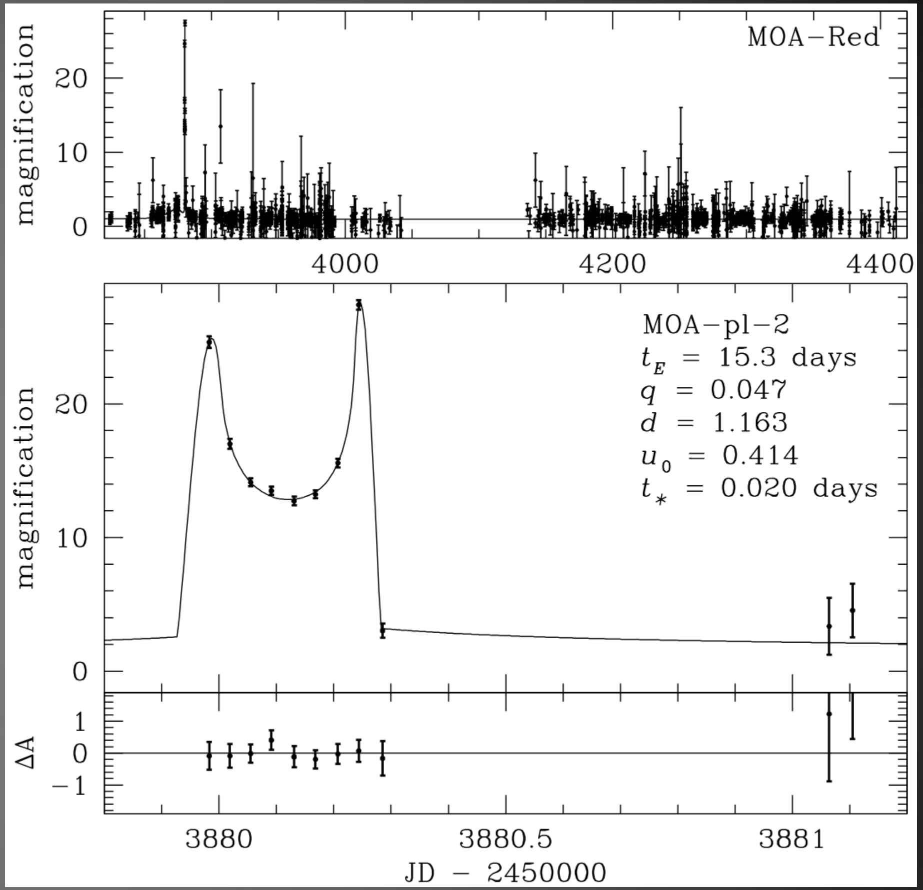
A_{max}= 30 event is separated from host star by > 15 R_E

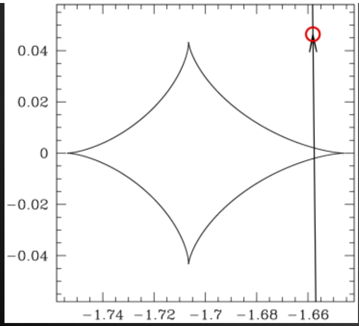
Binary Lens Background Rejection

- Both close ($d < R_E$) and wide ($d > R_E$) binary lens events can give rise to brief microlensing magnifications
- All short events can be fit by a wide binary model, because a wide binary approaches a single lens as d -> ∞
  - host stars must be at a distance > 3-15 R_E, depending on the event
  - high magnification events have the tightest limits
  - 2 wide binaries fail light curve shape cuts
- Close binaries have small external caustics that can also give short events
  - 1 such event passed all cuts but the light curve fit.
  - Close binary models have different, usually asymmetric, light curves
  - Close binary models can be rejected for all t_E< 2 day events, except for event 5
  - Since only 1 of 13 short events is a close binary, event 5 is probably a single lens event

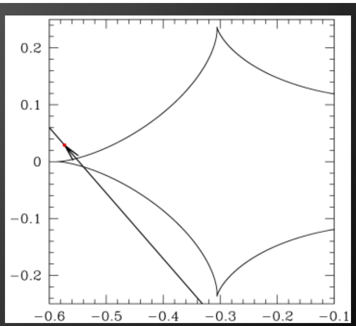
Background: Short Binary Events



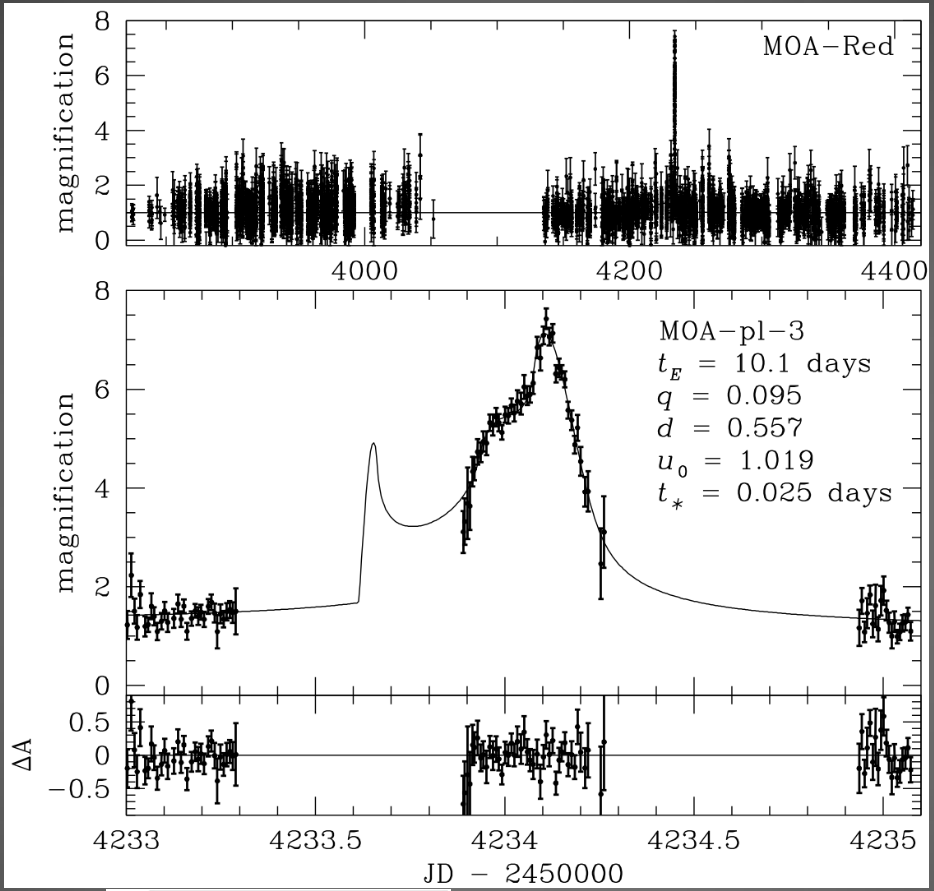


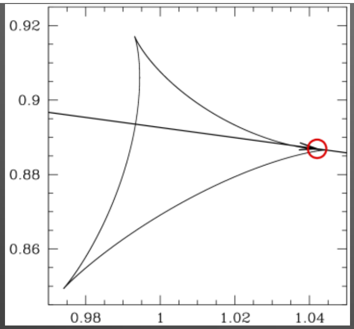


Wide-binaries (d = 2.2, 1.2) with planetary and brown dwarf mass ratios of q = 0.013 and 0.047



Background: Short Binary



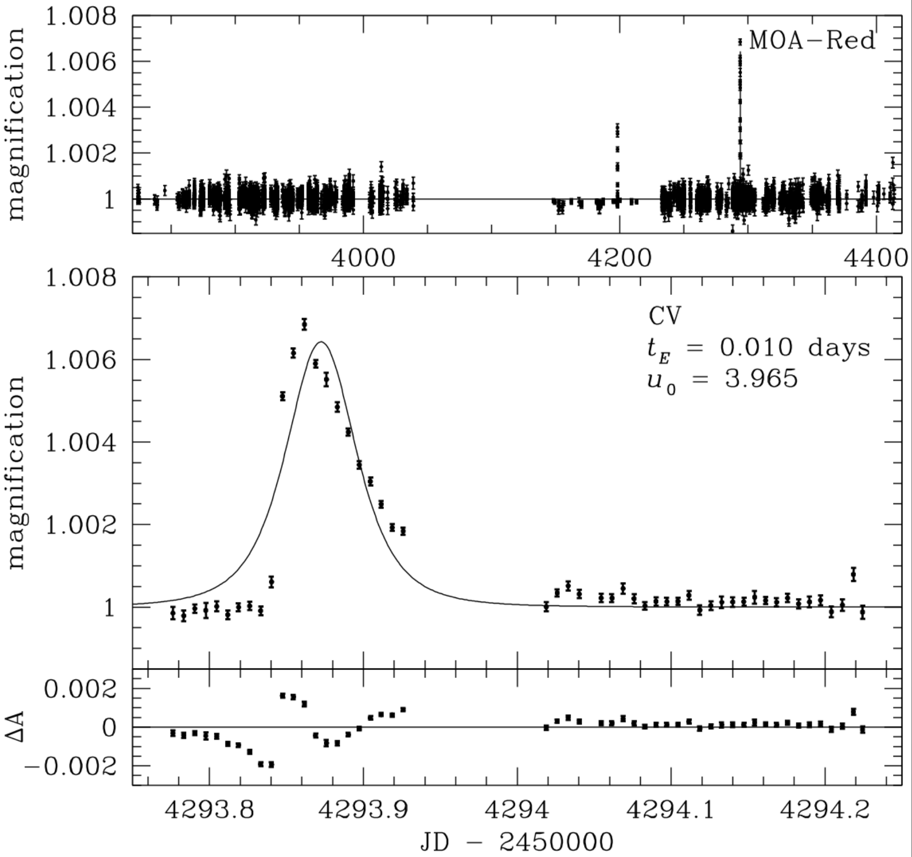


Close-binary (*d* = 0.56) with *q* = 0.095

CV Background Rejection

- Poor fit to microlensing event or unphysical source brightness
- Repeating
- 208 of 418 CV light curves in 2006-2007 data have a 2nd outburst in 2006-2010
  - Classified by eye from rejected events
  - 421 multiple outbursts fit to microlensing from multiple outburst events
  - All 421 failed to pass the cuts
- after analysis was complete, OGLE-III, II, I, and MACHO databases were checked
  - OGLE-III data confirms lens models for events 2, 3, 4, 6, 7, 8 and 9
  - OGLE-III 2002-2008 data shows no additional outburst back to 2002 for events 2, 3, 4, 5, 6, 7, 8, and 9
  - Events 3, 5, 6, and 8 show no outburst in 1990s – MACHO

Background: CV



a CV gives a poor microlensing fit, often with low magnification and an unphysically bright source

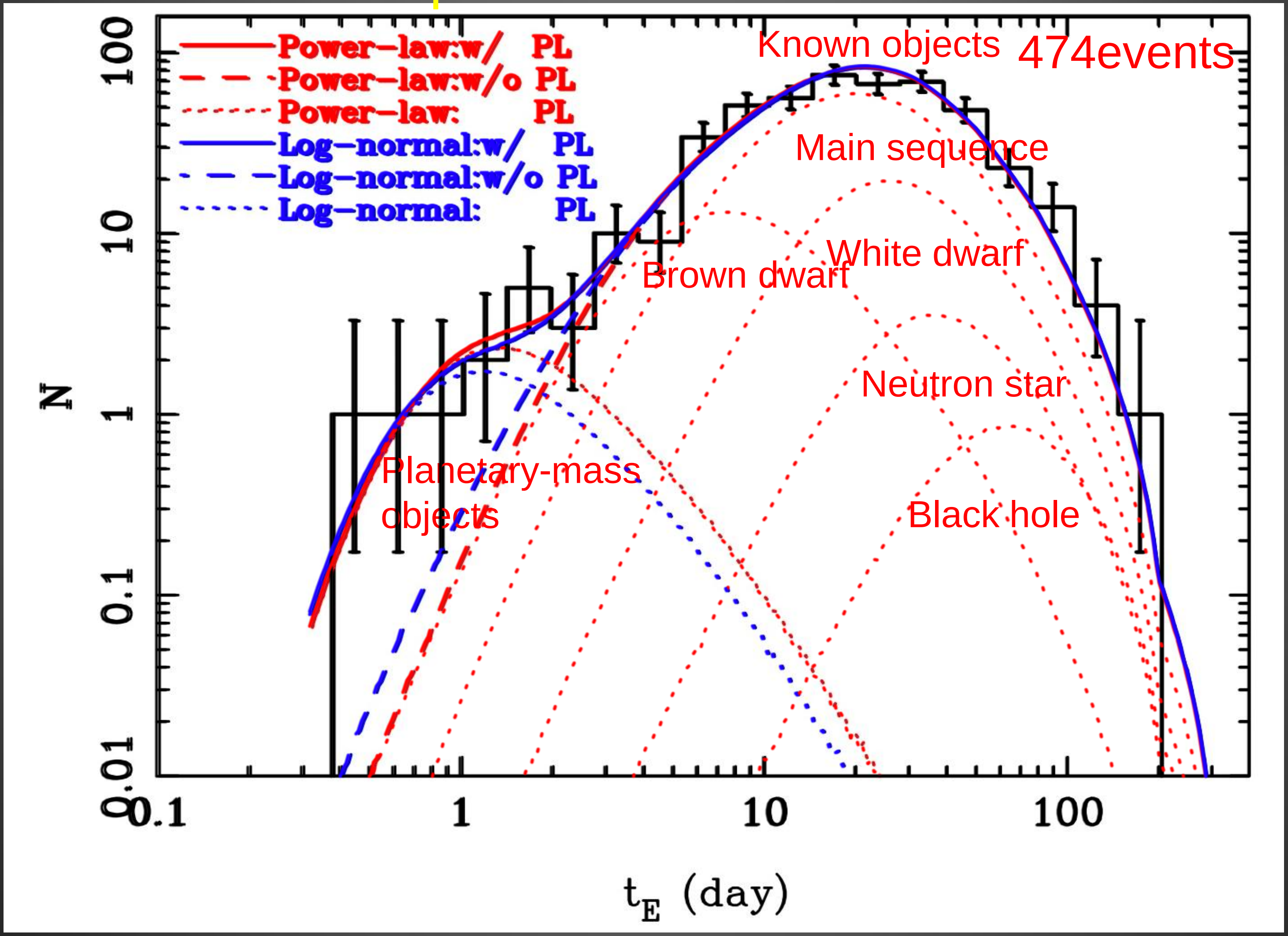
Timescale t_E distribution

abundance :~1.8 as common as stars

Mass : ∽Jupiter mass

$$N_{planet} = 1.8^{+1.7}_{-0.8} N_{star}$$

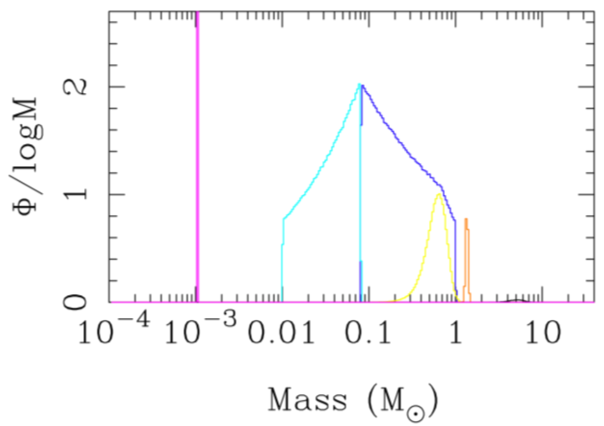
$$M_{planet} = 1.1^{+1.2}_{-0.6} M_J$$



Sumi et al. 2011, Nature, 473, 7347, 349-352

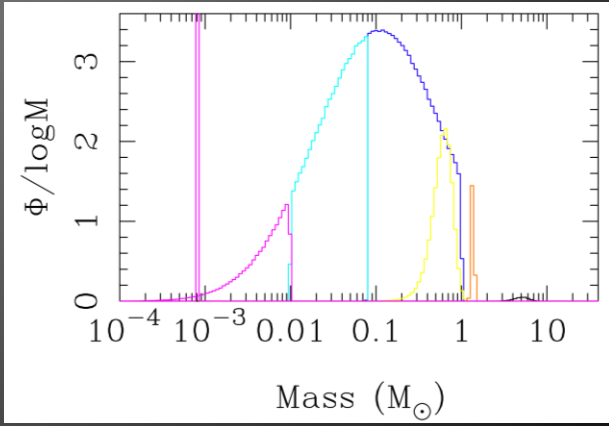
Mass Function Models

- Stars >1 $M_\odot$ have become stellar remnants
- Assume Salpeter-like slope (α = -2) for initial >1 $M_\odot$ stars
- Two choices at < 1 $M_\odot$
  - Broken power law
    - α = -2 for M > 0.7 $M_\odot$
    - α = -1.3 for 0.7 $M_\odot$> M > 0.08 $M_\odot$
    - α = -0.52 for 0.08 $M_\odot$> M > 0.01 $M_\odot$



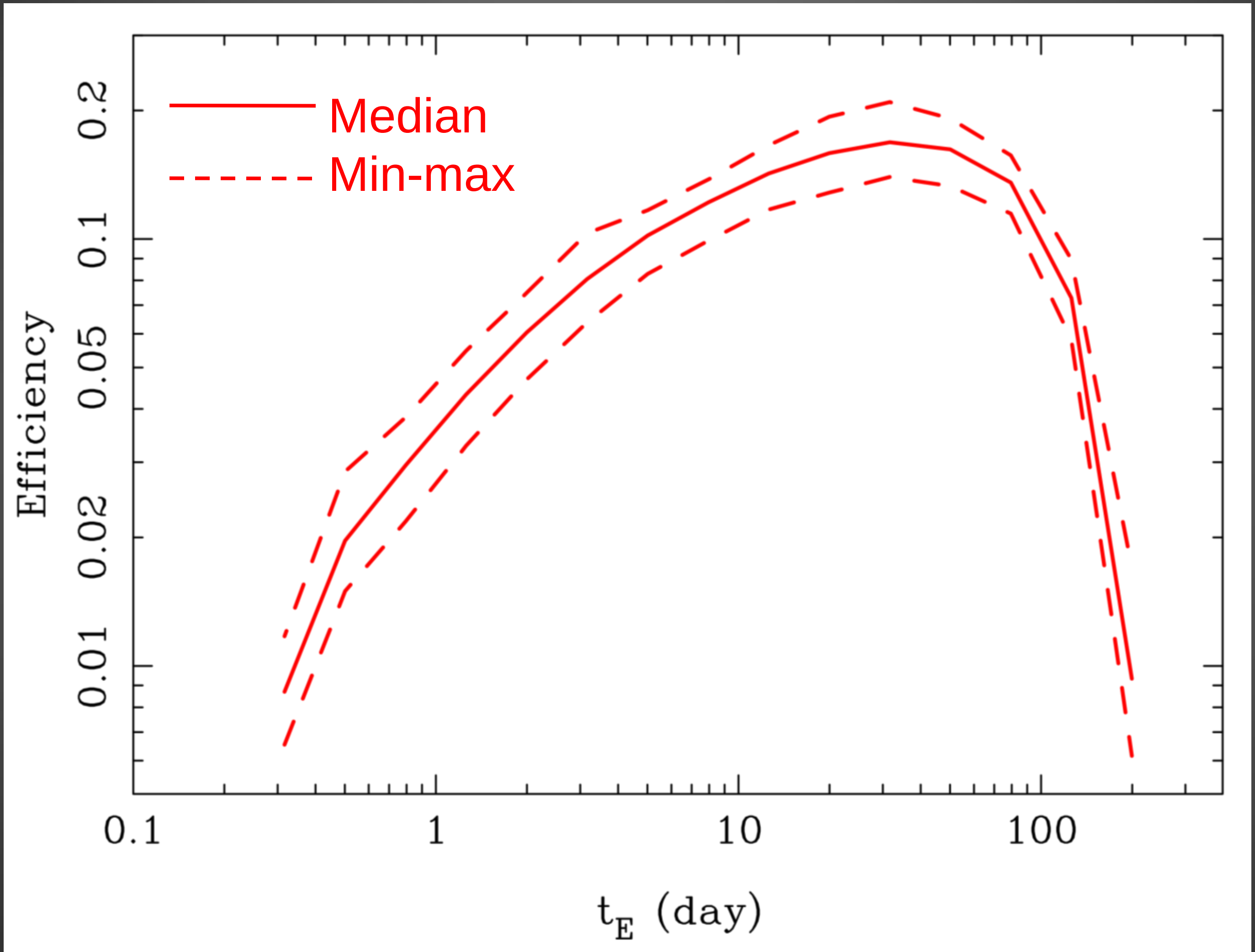
  - Chabrier log-normal
    - M_c= 0.12 $M_\odot$, σ_c = 0.76

$$dN/d\log M = \exp[(\log M - \log M_c)^2/(2\sigma_c^2)]$$

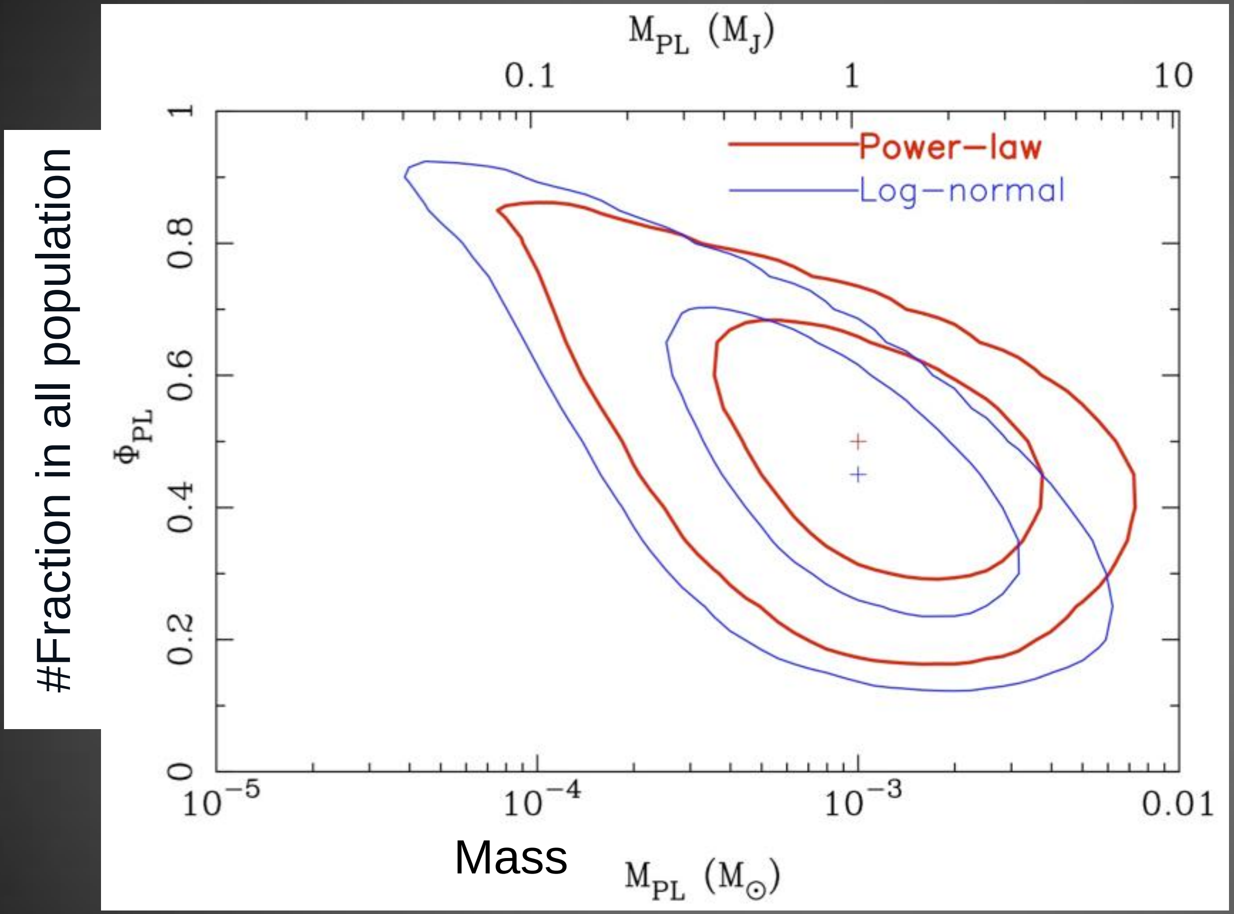


  - Planetary δ-function in mass
    - mass resolution limited by factor of 2-3 precision in t_E – mass relation

Detection Efficiency



Planetary Mass Function Parameters



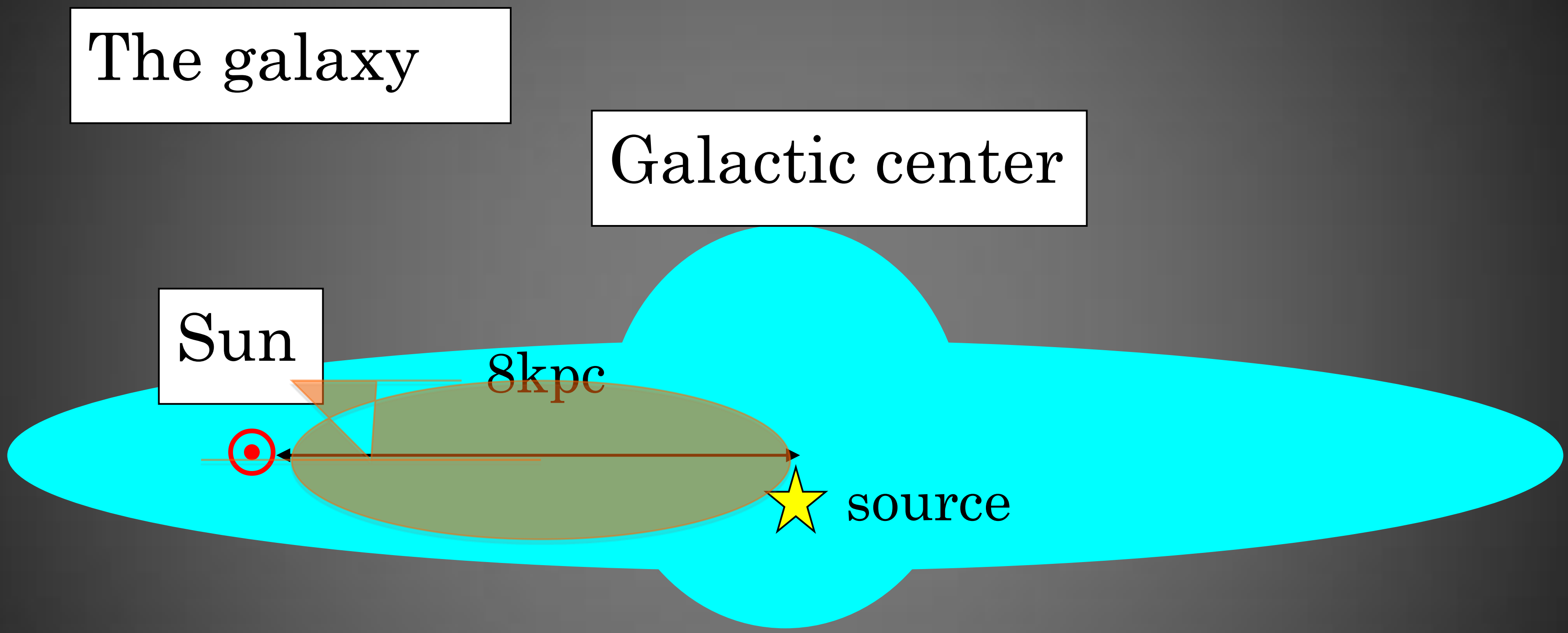
68%, 90% contour

$$Power-law: M_{PL} = 1.1^{+1.2}_{-0.6} \times 10^{-3}, \quad \Phi_{PL} = 0.49^{+0.13}_{-0.13}, \Rightarrow N/N_* = 1.9 \pm 0.5$$

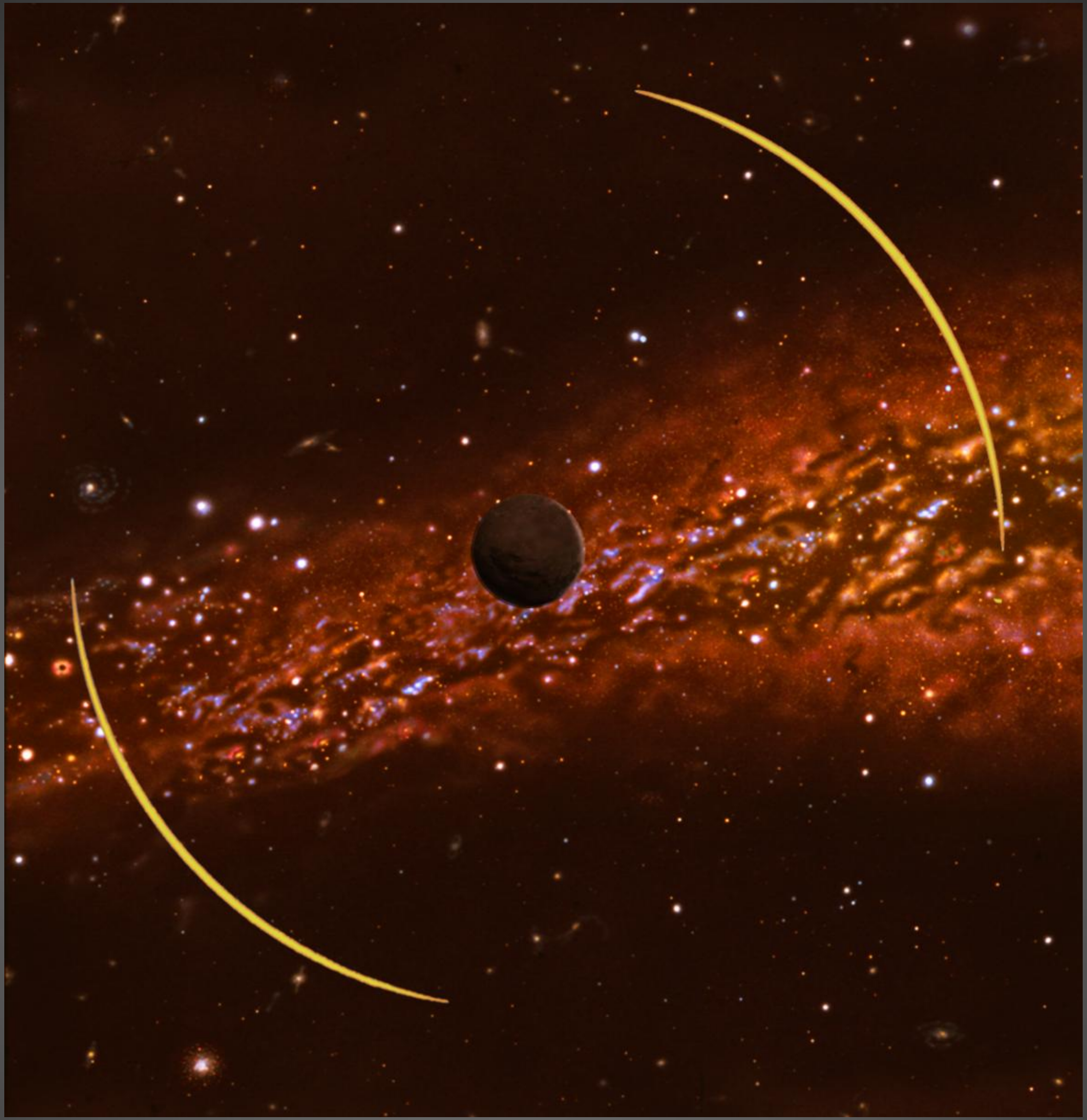
$$\log-normal: M_{PL} = 0.83^{+0.96}_{-0.51} \times 10^{-3}, \quad \Phi_{PL} = 0.46^{+0.17}_{-0.15}, \Rightarrow N/N_* = 1.8 \pm 0.6$$

1.8 isolated planets per star!

Where are they?



Somewhere between Sun and the galactic center

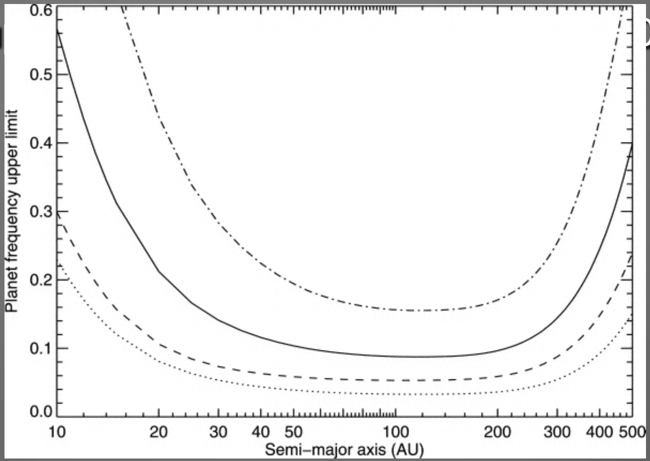


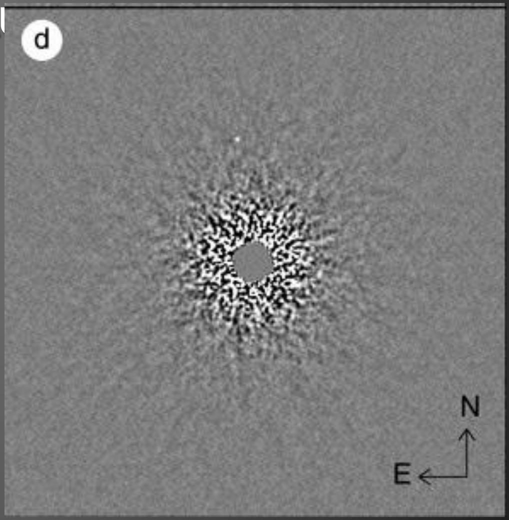
Far-infrared rendition of the Jovian-mass planet MOA-ip-10. It is either free-floating or extremely distant from its host star, and thousands of light-years away towards the galactic center. The planet's gravity creates Einstein arcs of a background star. Artwork by Jon Lomberg.

Unbound or distant planets?

- Microlensing data only sets a lower limit on the separation: no host stars within 10AU
  - HST follow-up can set tighter limits or detect host

  - 8 m telescope, Direct imaging limits （ Lafreniere et al. 2007)
    - < 40% of stars have 1 Ju





- We find 1.8 planets per star,

➔ so at least 1.4 planets per star (75%) should be free!

Isolated vs. Bound Planets

(Isolated means no detectable host – either free-floating or in a distant orbit > 7-45 AU depending on the event)

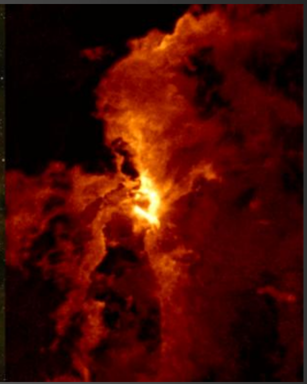
- Log-normal mass function implies 8 planets (plus 3 planetary mass brown dwarfs)
- Also, 5 planet+star events in the sample
  - So, a isolated:bound ratio of 8/5 = 1.6
- We can also compare to measurements of Cumming et al. (2008) and Gould et al. (2010) inside and outside the snow-line
  - Implies 1.2 Saturn-Jupiter mass planets per star at 0.03-10 AU
  - So, isolated:bound ratio ~ 1.8/1.2 = 1.5

- **More isolated planets than bound**
- **(At least comparable)**

Formation Scenarios:

1. formed on their own through gas cloud collapse similar to star formation (sub brown dwarf) ➔





- Hard to form Jupiter-mass objects
- Planetary-mass sub brown dwarf can explain only 1 or 2 short events.
- Abrupt change in mass function at Jupiter-mass do not support this scenario.

2. formed around a host star, and scattered out from orbit

Hot Jupiters orbiting hot stars have high obliquities (Winn et al. 2010, Triaud et al. 2010)

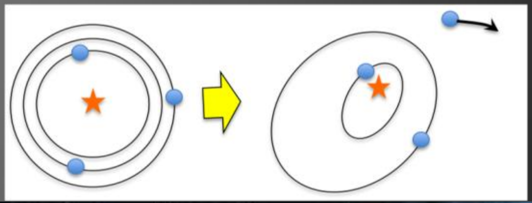
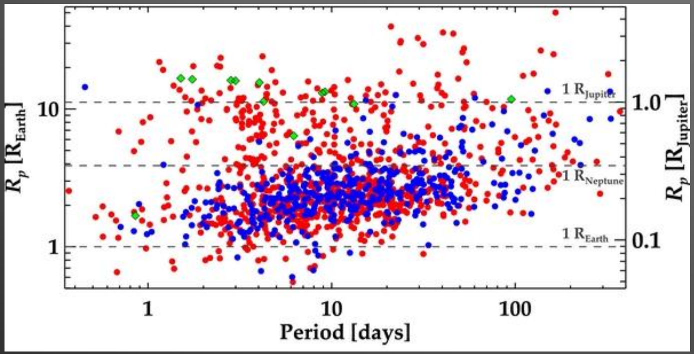
➔ evidence of gravitational interaction

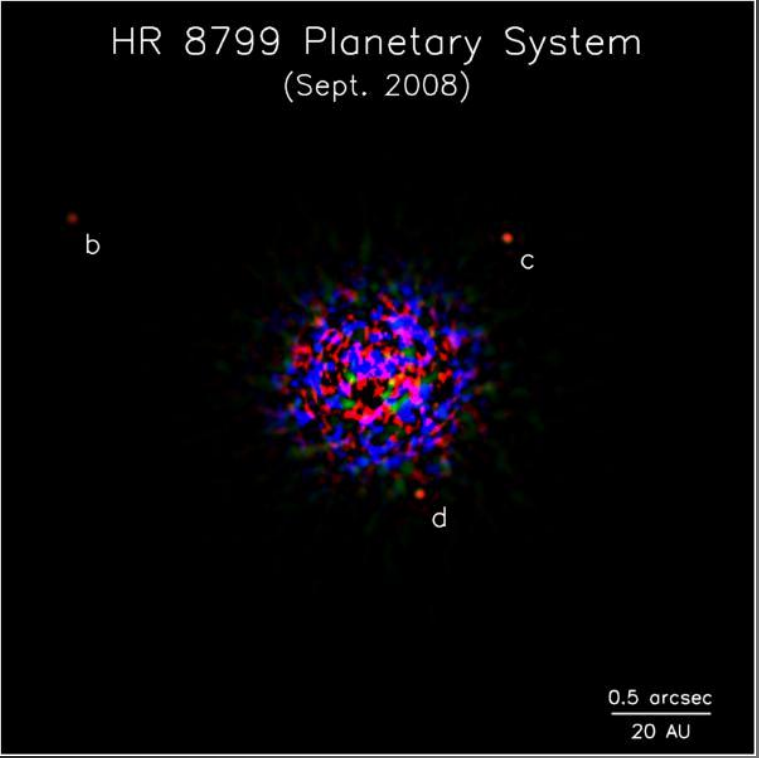
Hot Jupiters are alone (Latham et al. 2011)

➔ evidence of gravitational interaction

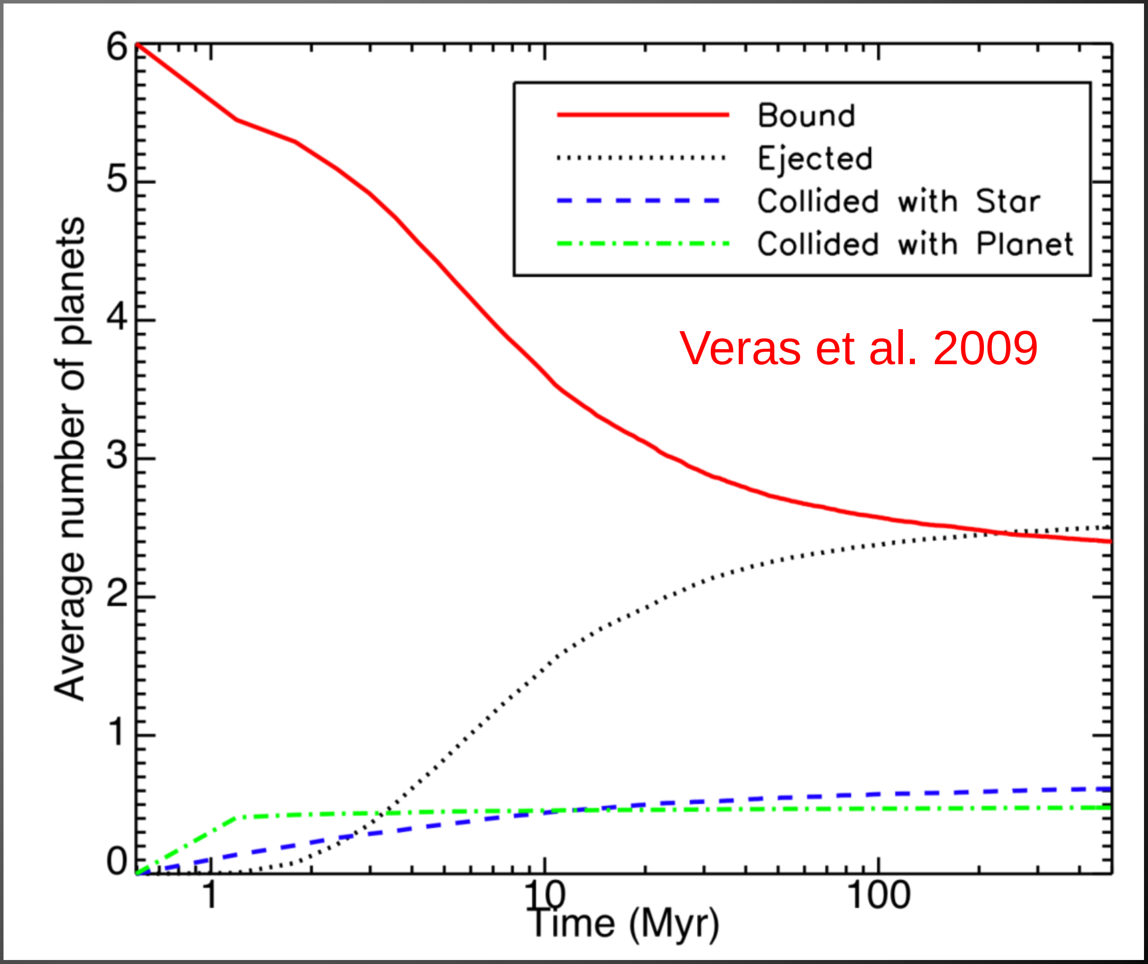
No desert for short-period super-earths (Howard et al. 2010)

➔**planet-disk interactions are of secondary importance to planet-planet scattering**

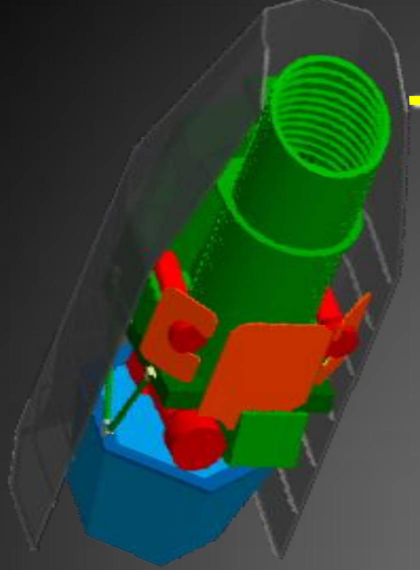





By Keck, Gmini, AO (**Marois et al.2008**)
M_{host}=1.5Msun(Atyp)
D~39pc
0.1 billion years old
M_p=10, 10 and 7 M_J
a=24, 37 and 67AU; ($a_{Neptune}$=30AU)

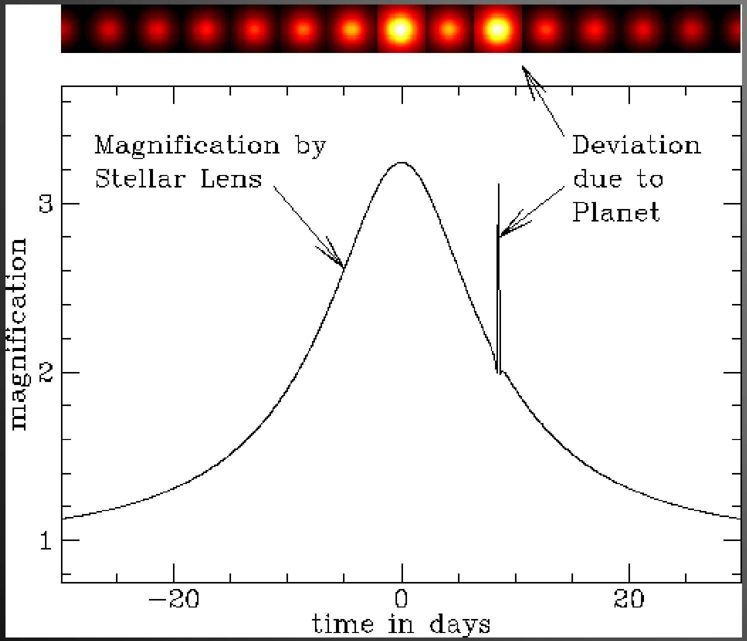


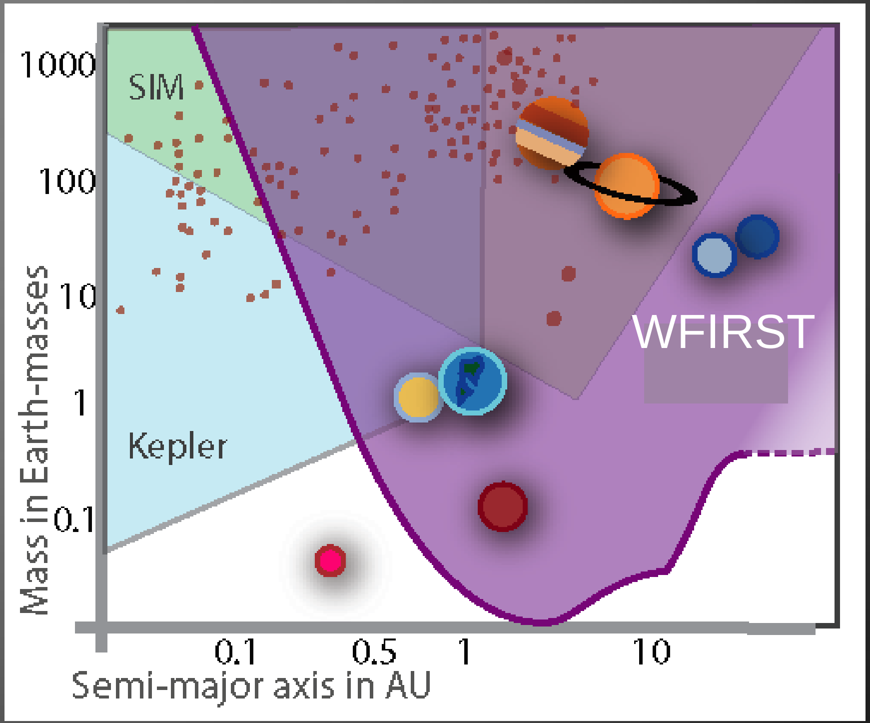
- half planets ejected after 10^7yr
- Free floating
- Microlensing can find



The WFIRST Microlensing Exoplanet Survey:

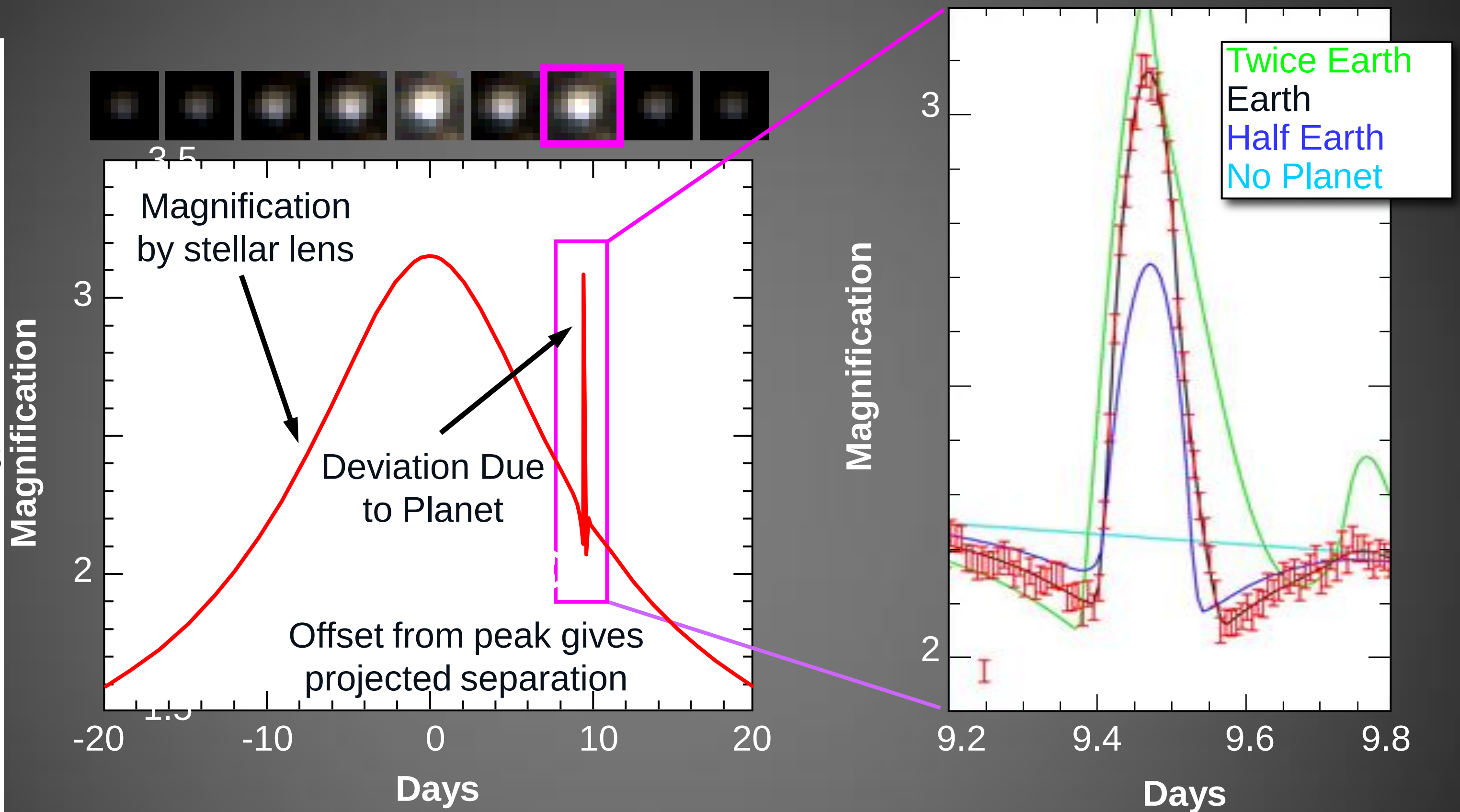
Recommended by ASTRO 2010 Decadal report





Simulated **WFIRST** Planetary Light Curves

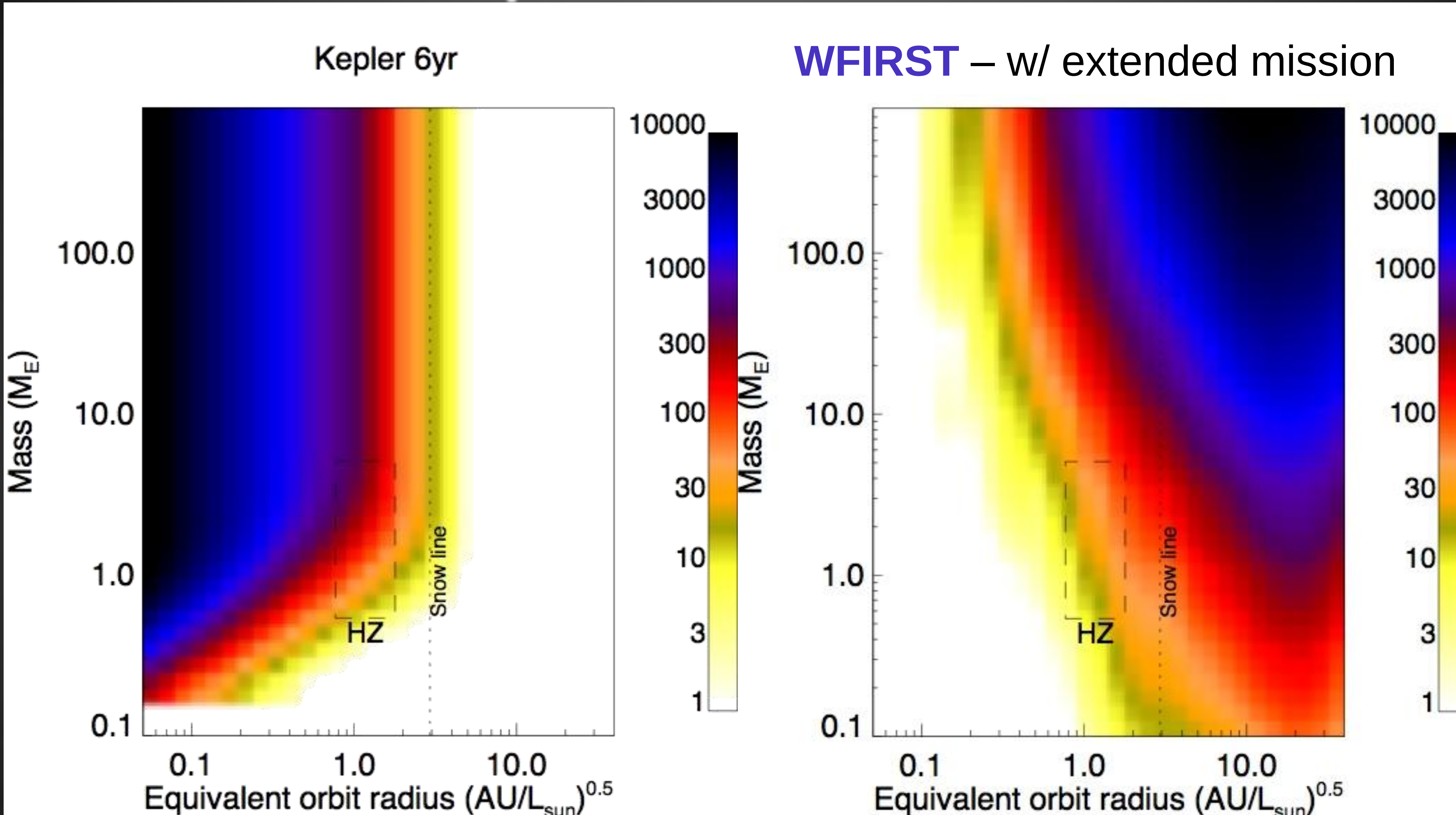
Time-series photometry is combined to uncover light curves of background source stars being lensed by foreground stars in the disk and bulge.



Planets are revealed as short-duration deviations from the smooth, symmetric magnification of the source due to the primary star.

Detailed fitting to the photometry yields the parameters of the detected planets.

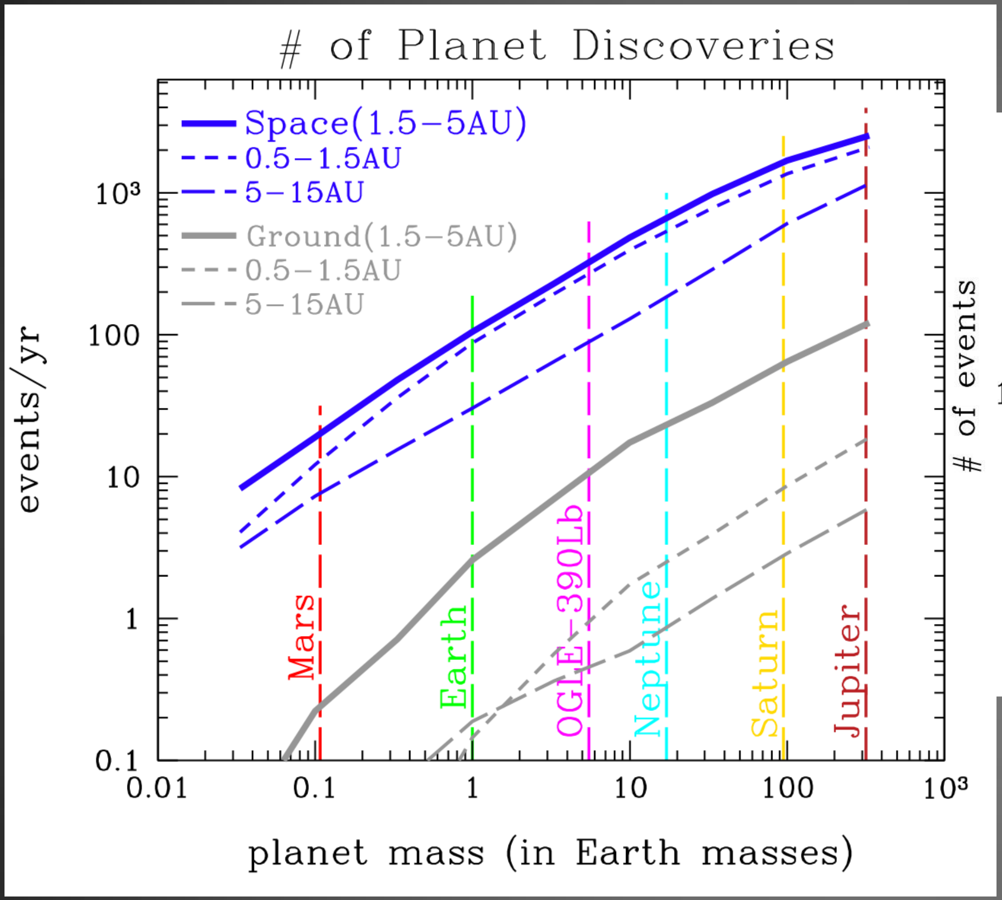
Kepler vs. WFIRST

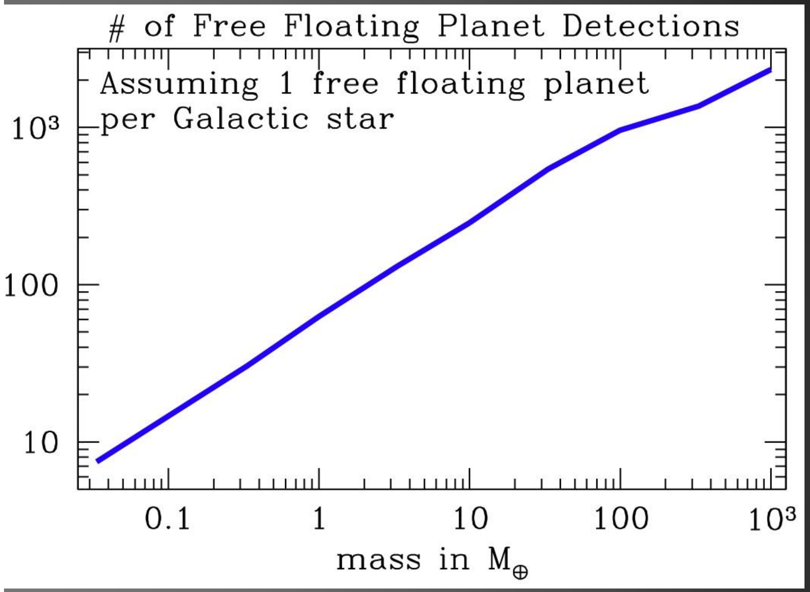


Figures from B. MacIntosh of the ExoPlanet Task Force

Complete the census of planetary systems in the Galaxy

WFIRST's Predicted Discoveries



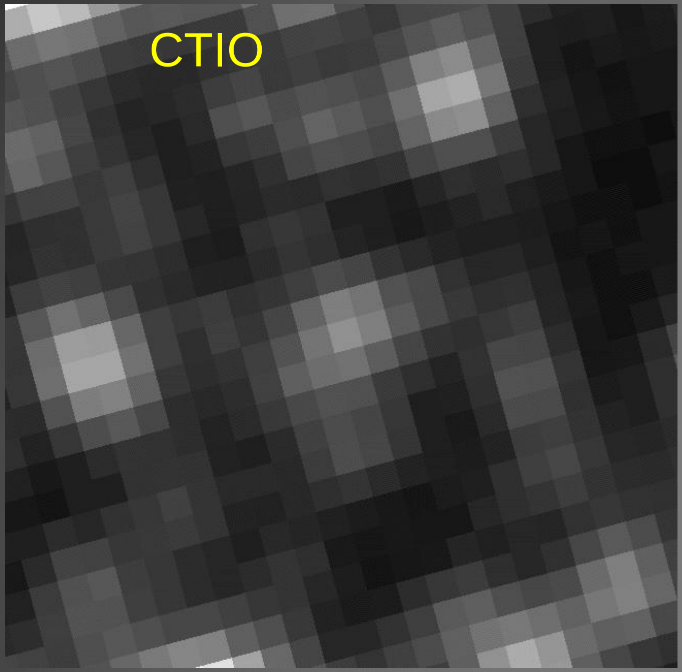


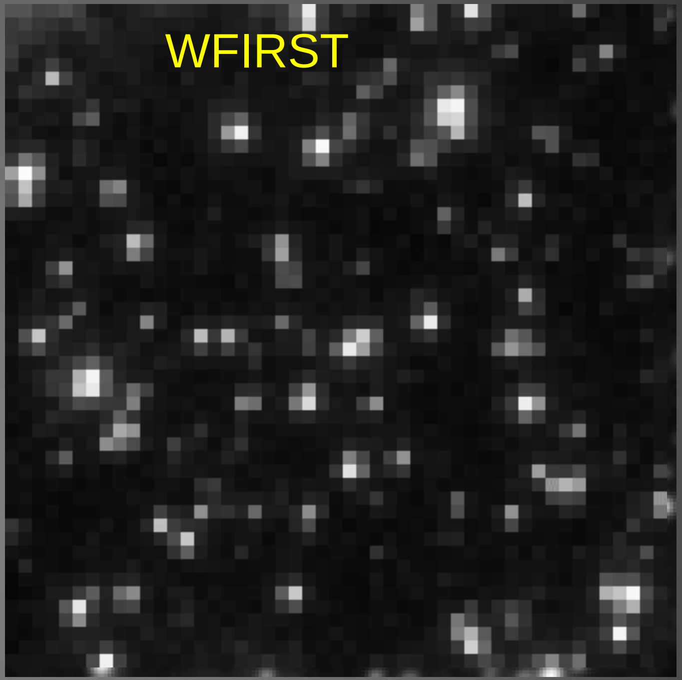
~2000 FFP！
~190 sub Eath-mass FFP!
(>30 Earth-mass FFP！)

~3000 exoplanets
~300 sub Earth-mass Planets,
>25 habitable planets
（0.5-10 M_{Earh}、0.72-2.0 AU）
around FGK stars

Free-floating rocky planets may have liquid water, Stevenson (1999)

Ground-based confusion, space-based resolution





- Space-based imaging needed for high precision photometry of main sequence source stars (at low magnification) and lens star detection
- High Resolution + large field + 24hr duty cycle => Microlensing Planet Finder (MPF)
- Space observations needed for sensitivity at a range of separations and mass determinations

Summary

- Free-floating planets are 1.8 times as common as main sequence stars (at least same order), and 1.5 times as common as bound planets。
- They may have formed in proto-planetary disks and subsequently scattered into unbound or very distant orbits
- They inform us not only the number of planets that survived in orbit, but also planets that formed earlier and scattered.

  ➔important for planetary formation theory
- WFIRST will detect >30 Earth-mass FFP